Agave: a promising feedstock for biofuels in the water-energy-food-environment (WEFE) nexus

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Abstract

The aim of this study was to conduct the first comprehensive life cycle assessment and economic analysis on ethanol produced from agave. Compositional and field data from a field experiment in Queensland, Australia was used. Our study shows that ethanol yields from agave (7414 L/ha/year) are comparable to Brazilian sugarcane (9900/L/ha/year) and higher than US corn ethanol (3800/L/ha/year). Furthermore, agave outperforms current first generation biofuel crops in water-related impacts, including Freshwater Eutrophication (96% lower than corn and 88% lower than sugarcane), Marine Ecotoxicity (59% lower than corn and 53% lower than sugarcane) and Water Consumption (46% lower than corn and 69% lower than sugarcane). The life cycle fossil energy use (Fossil Resource Scarcity) for agave is 58% lower than corn and 6% higher than sugarcane. The Global Warming impact for agave is also 62% and 30% lower than that of corn and sugarcane, respectively. Although its Land Use impact, measured by land occupied per unit ethanol output, is 98% higher than corn and 2% higher than sugarcane, agave can be grown on arid land that is not suitable for food crops. The economic analysis suggests that first generation ethanol production from agave is not commercially viable without government support. Overall, the results show that agave is promising for biofuel production in the water-energy-food-environment context.

Key words: Agave; biofuel; environmental impact; life cycle analysis (LCA); water-energy-food-environment (WEFE)

Abbreviations: 1G, 1st generation biofuel; 2G, 2nd generation biofuel; 3y, 2.5-year-old plants; 5y, 4.5-year-old plants; AusLCI, Australian National Life Cycle Inventory

Database; GHG, greenhouse gas; LCA, life cycle analysis; LCIA, life cycle impact assessment; LCI, life cycle inventory; L/ha/y, litres/hectare/year; NPV, net present value; N_2O, nitrous oxide; WEF, water-energy-food; WEFE, water-energy-food-environment; WSC, water soluble carbohydrate

1. Introduction

The water-energy-food-environment (WEFE) nexus is a huge challenge for the transition from a fossil fuel-dominated energy system to a more renewable and clean energy-based one. Although biomass is a renewable energy source that can potentially contribute to energy security goals, there are growing concerns over the sustainability of large-scale use of bioenergy (Popp et al., 2014). Its impacts on food security and food prices (Naylor et al., 2007), fresh water resources (Gerbens-Leenes et al., 2009) and many ecosystem services (Holland et al., 2015) have all been under increasing scrutiny recently while its net climate effects in many cases are still disputed mainly due to significant uncertainties in the associated indirect effects (e.g., potential changes in land systems (Searchinger et al., 2008) and food markets (Searchinger et al., 2015)) and nitrous oxide (N_2O) emissions from nitrogen fertiliser use (Crutzen et al., 2016).

Agave could be a promising bioenergy feedstock (Somerville et al., 2010) given its potentially high productivities, ability to thrive in semiarid regions, high water-use efficiency and low requirements for nitrogen fertilisers (Davis et al., 2011). Furthermore, its high sugar and low-lignin content make it an attractive crop from a bioprocessing perspective (Aleman-Nava et al., 2018). A seminal life cycle analysis (LCA) shows that ethanol derived from agave could offer higher land-use efficiencies and greenhouse gas (GHG) savings than ethanol produced from corn and switchgrass (Yan et al., 2011). However, this LCA study, the only one on agave-derived biofuels to date, is based on a hypothetical ethanol plant in Mexico using 1st generation (1G) conversion technology only (i.e., hydrolysis and fermentation of simple sugars extracted from the stem and leaves) and the agave and sugar yield data was sourced from literature on tequila production. Moreover, it focused only on energy and GHG analysis. In fact, comprehensive reviews (Davis et al., 2015, Cushman et al., 2015) on the use of bioenergy feedstocks including agave have confirmed that Yan et al., (2001) is currently the only LCA available on agave-derived biofuels and there is a need for a more comprehensive study. Building on Yan et al. (2011), an LCA was conducted for the possibility of integrating solar panels and annual agave production with synergies provided by water inputs for cleaning solar panels being similar to the water requirements for agave (Ravi et al., 2014). This LCA suggested that the hypothetical co-location of solar panels provided higher returns per m^3 of water used than either system alone. Preliminary economic studies were also conducted on agave for bioenergy production in Mexico (Nunez et al., 2011) and Australia (Subedi et al., 2017) based on hypothetical scenarios. To better understand the environmental and economic performance of agave-derived biofuels a comprehensive study using production and compositional data from long-term field experiments is required.

The aim of this paper was to conduct the first comprehensive LCA and economic analysis of 1st and 2nd generation (2G) ethanol produced from agave grown in Australia, using data collected from a 5-year field experiment in Queensland. The key novelties of our study therefore include the use of agave yield and sugar content data collected from a field experiment as well as the consideration of 2nd generation ethanol production. Australia has the largest proportion of semiarid land in the world (Davis et al., 2011). These areas do not support the growth of common agricultural crops but are suited for plants that thrive on marginal and dry lands, such as agave. Results from the LCA will be discussed in the context of the water-energy-food-environment (WEFE) nexus. The finding from this paper is expected to inform large-scale development of agave-based ethanol in Australia and other countries with significant amounts of semiarid land.

2. Materials and Methods

2.1 Agave field experiment in Australia

This LCA study was based on data from a pilot agave field experimental site at Kalamia Estate in the Burdekin River Irrigation System, near Ayr, Queensland (see Figure 1). The site is in a region with tropical savanna climate. The annual average temperature, based on recordings from the nearest weather station (Ayr DPI Research Station 33002), is 23.9 °C and precipitation is 947 mm dominated by summer rainfall with very little rain in the winter (Australian Government Bureau of Meteorology, 2018). For the field experiment 3500 plants were planted in June 2009 from tissue cultured agave (*Agave tequilana* Weber cv. *azul*) imported from Mexico by Mr Don Chambers of AusAgave (Holtum et al., 2011).

Figure 1 Pilot agave field experimental site at Kalamia Estate

As the experimental site was previously used for sugarcane and fruit (trees) production, land preparation only included pre-planting operations such as laser levelling, deep ripping, disc harrowing, rotary hoeing, bed forming and mulching. Nitrogen (250 kg ha^{-1}) fertiliser and herbicides [Treflan® (trifluralin), Atradex® (atrazine), Gramoxone® (paraquat) and Roundup® (glyphosate)] were applied before planting. The plants were watered once before transplanting to aid establishment and no irrigation was used during the experiment.

The agave plants were established on 15 cm raised beds at a density of 4000 plants ha^{-1} at a row spacing of 1.8 m x 1.6 m. Every second row was thinned out (harvested) at Year 2 (2011), leaving a density of 2000 plants ha^{-1}. Treflan®, Atradex® and Roundup® at recommended registered rates were applied once a year during the growing season. Pruning was performed manually twice a year. The periodic removal of offshoots (also referred to as suckers or pups) is required to encourage piña (stem) growth. The process of removal can be mechanised in a commercial operation.

2.2 Measurements of agave yield and sugar content

Three individual agave plants were harvested from Kalamia Estate in 2012 and 2014. Harvesting was carried out semi-mechanically in this experiment but can be mechanised using a modified cane harvester and two haul-out trailers. At the time of harvest plants were 2.5-year-old (2012), referred to hereafter as 3y plants and 4.5-year-old (2014), referred to hereafter as 5y plants. Immediately upon harvest the roots were washed with pressurized water to remove excess dirt. The weight of the whole plant and the individual vegetative parts (leaves, roots, stem and offshoots) were recorded. A commercial shredder (Cutter-Grinder CG03; South Australia, Australia) was used to extract the juice from both the agave leaves and stems. Following shredding, the wet fibrous bagasse fraction was collected, and the residual juice was removed by crushing subsets (300 g) of the bagasse using a press metal cylinder. After crushing the 3y samples were placed in a 65 °C oven for one week and the final weight recorded. The bagasse pellets from the 5y plants were placed directly in the freezer (-20 °C) and later lyophilized (Labconco-Freezone, Missouri, United States).

The dried bagasse material (3y and 5y samples) was homogenized and particle size reduced using a 25 mL stainless steel grinding jar with one 7 mm steel ball. The grinding jars were shaken at 30 Hz for 3 min (Retsch mill MM400, Retsch GmbH; Haan, Germany). The ball-milled samples were extracted following a small-scale extraction method (Corbin et al., 2015). Briefly, the bagasse samples were extracted sequentially in water, 95% v/v ethanol and 70% v/v ethanol at 80°C for 15 min using a 1:5 ratio of biomass to extraction liquid and dried to a constant weight.

The water extracts were incubated with fructanase (Fructan HK-Megazyme: AOAC Method 999.03; International Ireland Ltd., Wicklow, Ireland) to hydrolyse fructan polymers, as previously described (Corbin et al., 2015). The glucose, fructose and sucrose in the extracts were quantified by hydrophilic interaction chromatography, using a Prevail Carbohydrate ES column (150 × 4.6 mm) on an Agilent 1200 series liquid chromatography instrument equipped with an evaporative light scattering detector (Alltech ELSD 800) (Corbin et al., 2015). Sample peak areas were compared to calibration curves of standard solutions.

For compositional analysis of agave bagasse samples, standardized National Renewable Energy Laboratory (NREL) analytical methods were followed (Sluiter et al., 2004, Sluiter et al., 2006, Sluiter et al., 2008) with minor changes, as previously described (Corbin et al., 2015).

2.3 Goal and scope of the life cycle assessment

The goal of the LCA is to assess the environmental impacts and economic costs of ethanol produced from agave grown in Australia in comparison with US corn ethanol and Brazilian sugarcane ethanol. The system boundary considered is field-to-gate, which includes the following main stages: crop cultivation and harvesting, feedstock transportation and ethanol production at biorefinery. Transportation of the agave plants from Mexico to Queensland is not included as this is only the case for the experiment rather than potential industrial scale production in the future. The functional unit is 1 GJ of fuel ethanol produced. LCA software SimaPro 8.4 (2018) was used to perform the calculations.

To compare different key production options, 4 scenarios are evaluated considering the use of either 3y or 5y plants for 1G or 1G+2G ethanol production. As agave has a naturally long growth cycle (5-8 years), there are significant financial risks for growers due to changing environmental and market conditions (Yan et al., 2011). Therefore, it might be desirable to harvest agave plants early to reduce investment risks. In scenarios 1 and 3, the agave plants are harvested at the end of the third year. All the agrochemical inputs, farm machinery use, and sugar yields are based on the 3y plants harvested in the field experiment. Similarly, in scenarios 2 and 4, the agave plants are harvested at the end of the fifth year and all data used correspond to the 5y plants harvested in the experiment.

As the technology for 2G ethanol production from cellulosic biomass is still not mature, we evaluate and compare scenarios that only involve 1G technology with those involving both 1G and 2G technologies. In all scenarios juice is assumed to be extracted from the agave stems and leaves using a diffuser system, following a previous study

(Yan et al., 2011). In the 1G ethanol scenarios (1 and 2), the juice is used to produce ethanol through enzymatic hydrolysis and fermentation. The bagasse generated from the extraction process is used as fuel for a cogeneration system to provide the process energy. In the 1G+2G ethanol scenarios (3 and 4), both the juice and bagasse are used to produce ethanol while the lignin residue is used as fuel. The system boundaries for the 1G only scenarios and 1G+2G scenarios are illustrated in Figure 2.

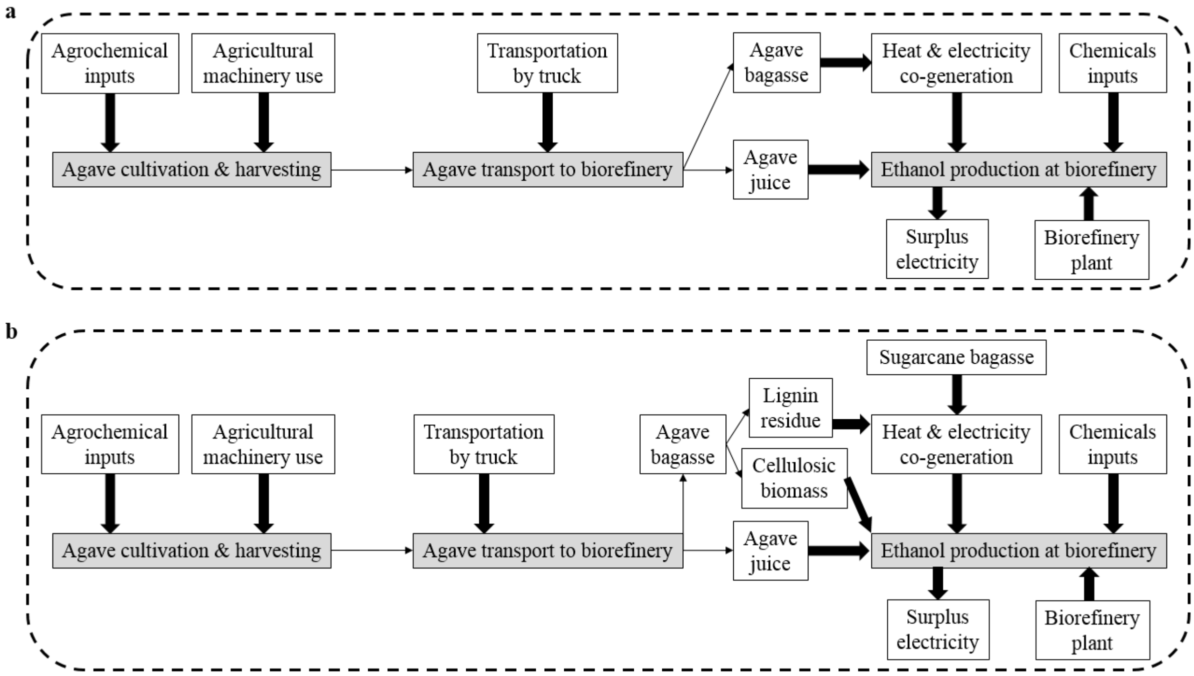

Figure 2 System boundaries for the 1G only scenarios (a) and 1G+2G scenarios (b)

2.4 Life cycle inventory and environmental impact assessment

The life cycle inventory (LCI) datasets for agave ethanol production are developed by modifying an existing dataset for Brazilian sugarcane ethanol production in the Ecoinvent LCI database within SimaPro. Key foreground inputs and their data sources are presented in the Supporting Information. The background datasets used are mainly from the Australian National Life Cycle Inventory Database (AusLCI, 2016) where possible, supplemented by the Ecoinvent database. Existing datasets for US corn ethanol and Brazilian sugarcane ethanol in the Ecoinvent database are used for comparison. The life cycle impact assessment method used is the ReCiPe 2016 Midpoint, which includes 17 impact categories (Huijbregts et al., 2016).

2.5 Economic analysis

The economic analysis used the same physical inputs in the LCA with unit costs in US$. The costing approach was similar to that of Subedi et al. (2017) except that actual field production costs for Kalamia Estate, Queensland were used in our study rather than a hypothetical farm of 37,000 ha over a 40-year investment cycle in Subedi et al. (2017). All input costings were provided by the farm manager on a per hectare basis and converted to the functional unit accordingly.

Ethanol plant operating cost was assumed to be US$0.4/L from an existing ethanol plant in the USA (Hofstrand, 2018). The base case for ethanol price was US$0.50/L based on the current ethanol price on the global market (Trading Economics, 2018). The production costs were calculated for 3y and 5y agave under the 1G scenario since 2G conversion technology is not yet mature in Australia (and costs are difficult to estimate). Net present value (NPV) was calculated using a 5% discount rate following Subedi et al. (2017).

3. Results and Discussion

3.1 Chemical analysis of agave

In this study, agave plants were harvested and characterized at two developmental stages, 3y and 5y. The different anatomic fractions of the plants were separated and crushed following harvest, yielding bagasse and juice fractions from the leaves, stem and offshoots (5y only). The offshoots were not separated from the leaf fraction of the 3y plants. The average above-ground fresh weight of 3y plants was 205 kg of which 88% was leaves and 12% stem biomass. For 5y agave plants the mass distribution was 45% leaves, 17% stem and 38% offshoots, averaging 361 kg (Corbin et al., 2016). Unlike other feedstocks which have been considered as dedicated biofuel crops, agaves are water-dense (85-95%) (Corbin et al., 2015, Li et al., 2012). Using a press metal cylinder 68%, 43% and 27% of the starting mass (% w/w) from leaf, stem and offshoot tissues, respectively, was collected as juice. Stem bagasse was found to accumulate non-structural sugars (free sugars, water soluble carbohydrates (WSC) and fructans) at a higher rate than leaf tissue. Furthermore, the amount of lignin in 5y plants was lower than 3y plants in both leaf and stem bagasse. Over a two-year period, there was a 35% increase in sugar accumulation in the leaf juice and a 64% increase measured in the stem juice (Corbin et al., 2016, Corbin et al., 2015). This finding indicates that the type and amount of sugar in agave juice is both origin (leaf vs stem) and age dependent. A detailed mass balance of the bagasse fractions is summarized in Table 1.

Table 1 Mass balance of *A. tequiliana* bagasse (% w/w)

Biomass	**Extractives**		**Composition of raw biomass**				**Total sugar (%)**	**Total mass accounted for**
	WSC*	Total extractives^	Cellulose	NCPs[$]	Lignin	Ash		
Leaf bagasse (3y)	4.3 ± 0.5	16.4 ± 4.2	26.1 ± 0.7	16.6 ± 0.7	17.0 ± 1.5	10.5 ± 0.8	*47.0*	*86.6*
Stem bagasse (3y)	8.9 ± 0.8	18.2 ± 1.8	22.3 ± 2. 2	16.5 ± 2.5	12.7 ± 3.9	16.2 ± 2.0	*47.7*	*85.9*
Leaf bagasse (5y)	12.2 ± 2.3	27.9 ± 2.0	26.5 ± 2.9	17.8 ± 5.9	13.4 ± 1.0	9.7 ± 1.0	*56.5*	*95.3*
Stem bagasse (5y)	42.7 ± 5.2	53.3 ± 5.5	10.6 ± 2.2	10.6 ± 1.3	6.2 ± 1.4	8.0 ± 1.1	*63.9*	*88.7*
Offshoot bagasse (5y)	15.7 ± 1.7	33.2 ± 3.1	19.8 ± 2.1	13.8 ± 1.7	13.1 ±1.6	11.1 ± 0.8	*49.3*	*91.0*

^ Combined water and ethanol extractions (includes soluble sugar, lignin, protein and ash).
* Water extracts were hydrolysed with fructanase prior to analysis
[$] NCPs: Non-cellulosic polysaccharide
Results for cellulose, NCPs, lignin and ash are reported as percentage of non-extracted biomass.

Italicized values are derived from calculation rather than direct measurement. Total sugar calculation includes WSC, cellulose and NCPs. Total mass is the sum of total extractives, cellulose, NCPs, lignin and ash. Data reported are the mean values of three replicates.

3.2 Estimated ethanol yield

We estimate potential ethanol yield based on data collected from the agave experiment, including weight of an agave plant and sugar contents presented above, as well as assumptions on the ethanol production process. The overall sugar utilisation efficiency is assumed to be 90% for 1G ethanol production (Yan et al., 2011) and 60% for 2G ethanol production as a range of 30% to 90% can be found in the literature (Kang et al., 2014, Limayem et al., 2012, Hamelinck et al., 2005). The yields of 1G ethanol from agave juice would be 4854 and 6673 L/ha/y for 3y and 5y agave plants, respectively (Table 2). These are higher than the ethanol yield of 3809 L/ha/y (81 GJ/ha/y) from 5y agave plants estimated in a previous study based on data from the Mexican tequila industry (Yan et al., 2011). If the bagasse is also used to produce 2G ethanol, yields would increase by 490 and 741 L/ha/y for 3y and 5y agave plants, respectively. Overall, the yields for 5y agave estimated in this study are comparable to sugarcane (6900 L/ha/y of 1G ethanol from juice and an additional 3000 L/ha/y of 2G ethanol from bagasse) and much higher than corn (2900 L/ha/y of 1G ethanol from grain and an additional 900 L/ha/y of 2G ethanol from stover) (Somerville et al., 2010).

Table 2 Estimates for ethanol production from agave

Measured data		**Age of plant**	
		3y	**5y**
Fresh weight of agave plant	kg/plant	205	361
1G sugar yield	kg/plant	10.4	25.8
2G sugar yield	kg/plant	1.6	4.3
Assumptions			
Overall 1G sugar utilisation efficiency		90%	90%

Overall 2G sugar utilisation efficiency		60%	60%
Theoretical ethanol yield from sugar	kg/kg sugar	0.51	0.51
Calculated data			
agave yield (fresh biomass)	t/ha	410	721
1G ethanol yield	L/ha/year	4854	6673
2G ethanol yield	L/ha/year	490	741

3.3 Life cycle assessment results

The LCA results for agave ethanol under the four production scenarios are shown in Table 3 (absolute values) and Figure 3 (relative values). Ethanol that is produced from 5y agave plants has lower impacts for all categories compared to that from 3y plants. This is mainly because of the relatively higher amounts of sugar and hence ethanol produced from the 5y plants in proportion to the inputs needed. In general, ethanol produced from the 1G only options have lower impacts than that from the 1G+2G options for all impact categories except Land Use. This is mainly because the 1G option produces significant amounts of surplus electricity from the bagasse and displaces grid electricity in Queensland, which is mainly generated from coal. For many categories such as Global Warming, Acidification and Ecotoxicity this even resulted in negative impacts (i.e. net benefits). The lower Land Use impacts of the 1G+2G options were because of their moderately higher ethanol yields per unit of land used.

Table 3 LCA results for ethanol produced from agave in Australia under different production options

Impact category	**Unit**	1G agave 3y	1G agave 5y	1G+2G agave 3y	1G+2G agave 5y
Global warming	kg CO_2 eq	-23.4	-70.0	28.0	5.1
Stratospheric ozone depletion	kg CFC11 eq	0.0002	0.0001	0.0002	0.0001
Ionizing radiation	kBq Co-60 eq	0.02	0.01	0.02	0.01
Ozone formation, Human health	kg NOx eq	0.05	-0.14	0.25	0.15
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.04	-0.01	0.08	0.06

Ozone formation, Terrestrial ecosystems	kg NOx eq	0.05	-0.14	0.25	0.15
Terrestrial acidification	kg SO_2 eq	-0.05	-0.25	0.18	0.07
Freshwater eutrophication	kg P eq	0.001	0.001	0.002	0.001
Terrestrial ecotoxicity	kg 1,4-DCB e	0.03	0.02	0.03	0.03
Freshwater ecotoxicity	kg 1,4-DCB e	-0.10	-0.48	0.36	0.19
Marine ecotoxicity	kg 1,4-DBC e	-0.08	-0.60	0.55	0.31
Human carcinogenic toxicity	kg 1,4-DBC e	0.31	0.03	0.54	0.35
Human non-carcinogenic toxicity	kg 1,4-DBC e	681	208	1129	848
Land use	m^{2}a crop eq	117	79	107	71
Mineral resource scarcity	kg Cu eq	0.10	0.06	0.11	0.07
Fossil resource scarcity	kg oil eq	4.5	-0.5	7.2	3.8
Water consumption	m^3	1.6	-6.7	10.0	5.7

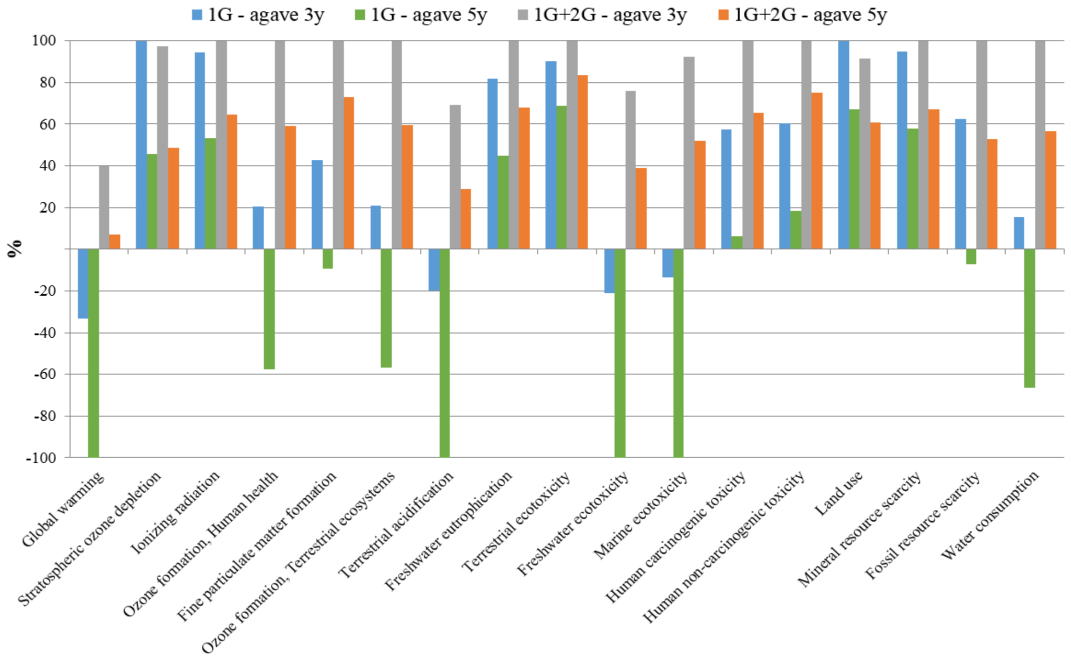

Figure 3 Normalised LCA results for ethanol produced from agave in Australia under different production options

Examining the contributions of main life cycle stages to different categories of impacts reveals interesting insights (Figure 4). The manufacturing and transport of agrochemical inputs such as fertilisers and pesticides contribute noticeably to Ionizing Radiation, Freshwater Eutrophication, Mineral Resource Scarcity and Water Consumption. An

LCA of the herbicide, diuron on agave farms in Mexico showed that the most environmentally friendly option was the one with the shortest transportation distance (Tirametoakkhara and Lerkkasemsan, 2019). Agricultural machinery use makes significant or noticeable contributions to most impact categories primarily because of diesel fuel consumption and emissions and metals used in machinery production. Agave growth dominates the Stratospheric Ozone Depletion (because of N_2O emissions from nitrogen fertiliser used) and Land Use impacts. Transport of agave to biorefinery, manufacturing and transport of biorefinery material inputs, and biorefinery infrastructure together contribute noticeably to Ionizing Radiation, Freshwater Eutrophication, Human Carcinogenic Toxicity, Mineral Resource Scarcity, Fossil Resource Scarcity and Water Consumption. Biorefinery operation contributes significantly to Ozone Formation, Fine Particulate Matter Formation and Terrestrial Ecotoxicity primarily because of the burning of bagasse for energy generation. Sizable contributions by biorefinery waste treatment can be seen for Freshwater Eutrophication, Freshwater Ecotoxicity, Marine Ecotoxicity and Human Non-carcinogenic Toxicity. Surplus electricity export can offset significant impacts for most categories in the case of the 1G ethanol options. However, the potential offsets in the case of the 1G+2G options are limited for 5y agave and insignificant for 3y agave because of much lower electricity generation.

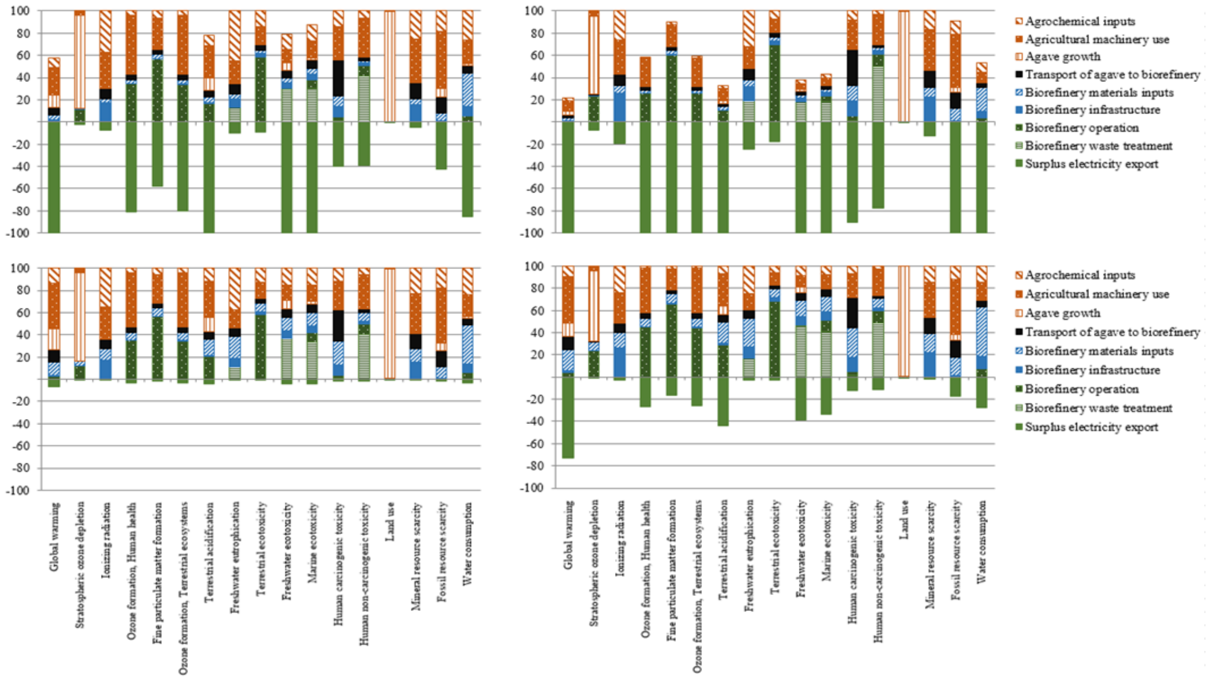

Figure 4 Contributions of main life cycle stages to the different categories of environmental impacts for ethanol produced from agave in Australia under different production options (unit:%): upper left- 1G agave 3y; upper right- 1G agave 5y; lower left- 1G+2G agave 3 y; and lower right- 1G+2G agave 5y

Comparison between ethanol produced from Australian agave, US corn and Brazilian sugarcane is shown in Table 4 and Figure 5. As existing datasets for US corn and Brazilian sugarcane ethanol available in the Ecoinvent LCI database only cover 1G ethanol production and do not consider surplus electricity generation, we compare them with 1G ethanol produced from 5y agave plants with surplus electricity generated from bagasse disregarded. The findings show that agave is the lowest in most impact categories except for Ozone Formation (higher than both corn and sugarcane), Terrestrial Ecotoxicity (higher than corn), Human Carcinogenic Toxicity (higher than corn), Land Use (higher than both corn and sugarcane) and Fossil Resource Scarcity (higher than sugarcane).

Table 4 LCA results for ethanol produced from agave in Australia (5y old plants with no surplus electricity generated from bagasse), corn in US and sugarcane in Brazil

Impact category	**Unit**	1G agave (5y) *no surplus electricity*	1G US corn	1G Brazil sugarcane
Global warming	kg CO_2 eq	19.1	50.0	27.2
Stratospheric ozone depletion	kg CFC11 eq	0.0001	0.0004	0.0002
Ionizing radiation	kBq Co-60 eq	0.01	2.49	0.71
Ozone formation, Human health	kg NOx eq	0.20	0.09	0.14
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.07	0.08	0.07
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.21	0.10	0.15
Terrestrial acidification	kg SO_2 eq	0.13	0.30	0.38
Freshwater eutrophication	kg P eq	0.001	0.021	0.007
Terrestrial ecotoxicity	kg 1,4-DCB e	0.03	0.02	0.04
Freshwater ecotoxicity	kg 1,4-DCB e	0.29	0.96	0.66
Marine ecotoxicity	kg 1,4-DBC e	0.45	1.10	0.95
Human carcinogenic toxicity	kg 1,4-DBC e	0.37	1.35	1.52
Human non-carcinogenic toxicity	kg 1,4-DBC e	928	484	3141
Land use	m^2a crop eq	79.3	40.1	77.6
Mineral resource scarcity	kg Cu eq	0.07	0.13	0.15
Fossil resource scarcity	kg oil eq	4.8	11.4	4.6
Water consumption	m^3	7.7	14.3	24.5

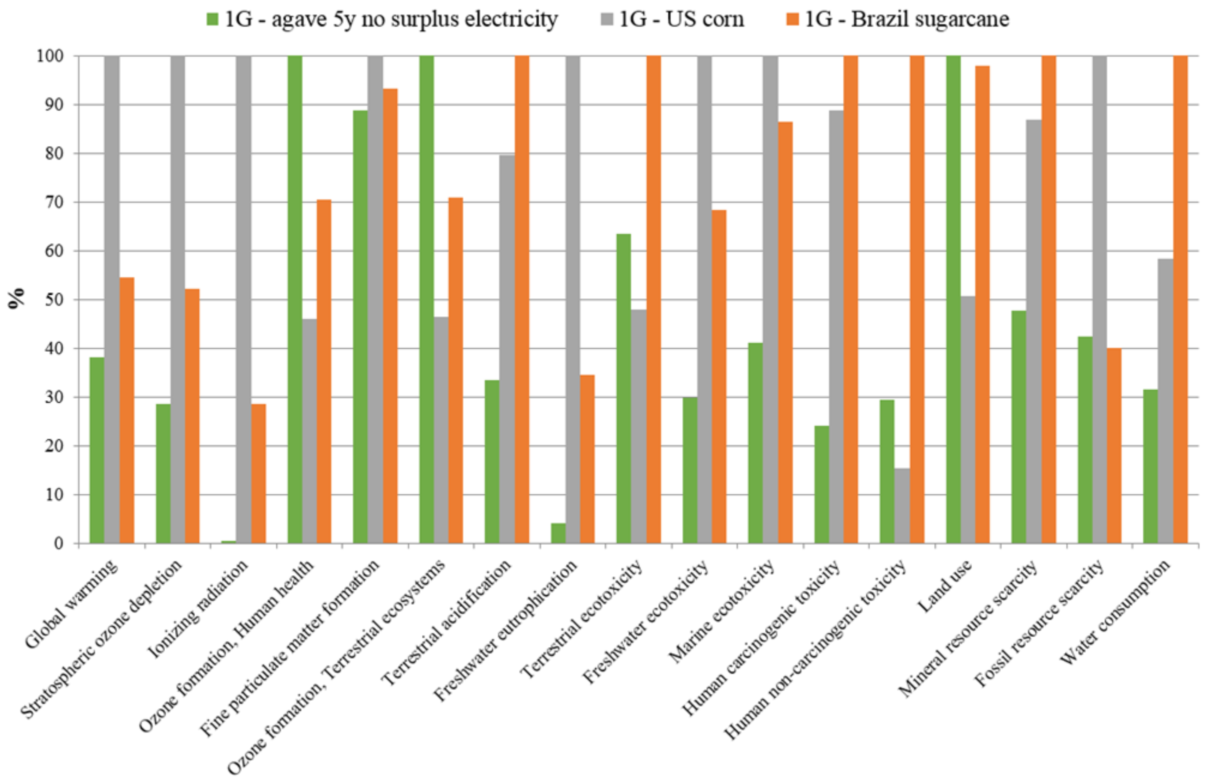

Figure 5 Normalised LCA results for ethanol produced from agave in Australia (5-year old plants with no surplus electricity generated from bagasse), corn in US and sugarcane in Brazil

The contributions of main life cycle stages to different categories of impacts vary significantly between agave, corn and sugarcane except for Land Use (Figure 6). For example, the contribution of biorefinery operation to Global Warming is sizable for corn as natural gas is used as the main energy source in US corn ethanol plants. This contribution is insignificant for agave and sugarcane as bagasse is used as an energy source. However, the combustion of bagasse makes the contribution of biorefinery operation to air pollution (i.e., Ozone Formation and Fine Particulate Matter Formation) much higher for agave and sugarcane than for corn. Land Use is dominated by crop growth for all three crops. The lower Land Use for corn is due to the assumed crop rotation in the Ecoinvent dataset for corn ethanol as well as the credit gained from the protein-rich coproduct used for animal feed. The yield of ethanol achieved from using agave biomass (6673 L/ha/y) and sugarcane (6900 L/ha/y) are still higher than corn (2900 L/ha/y). Water Consumption is dominated by irrigation during crop growth for corn and sugarcane. On the other hand, crop growth accounts for only 1% of agave's water consumption as the field was only irrigated once (first year) to facilitate plant establishment in the agave field experiment. In fact, the majority of life cycle water consumption for agave is due to the generation of hydropower consumed in various industrial processes.

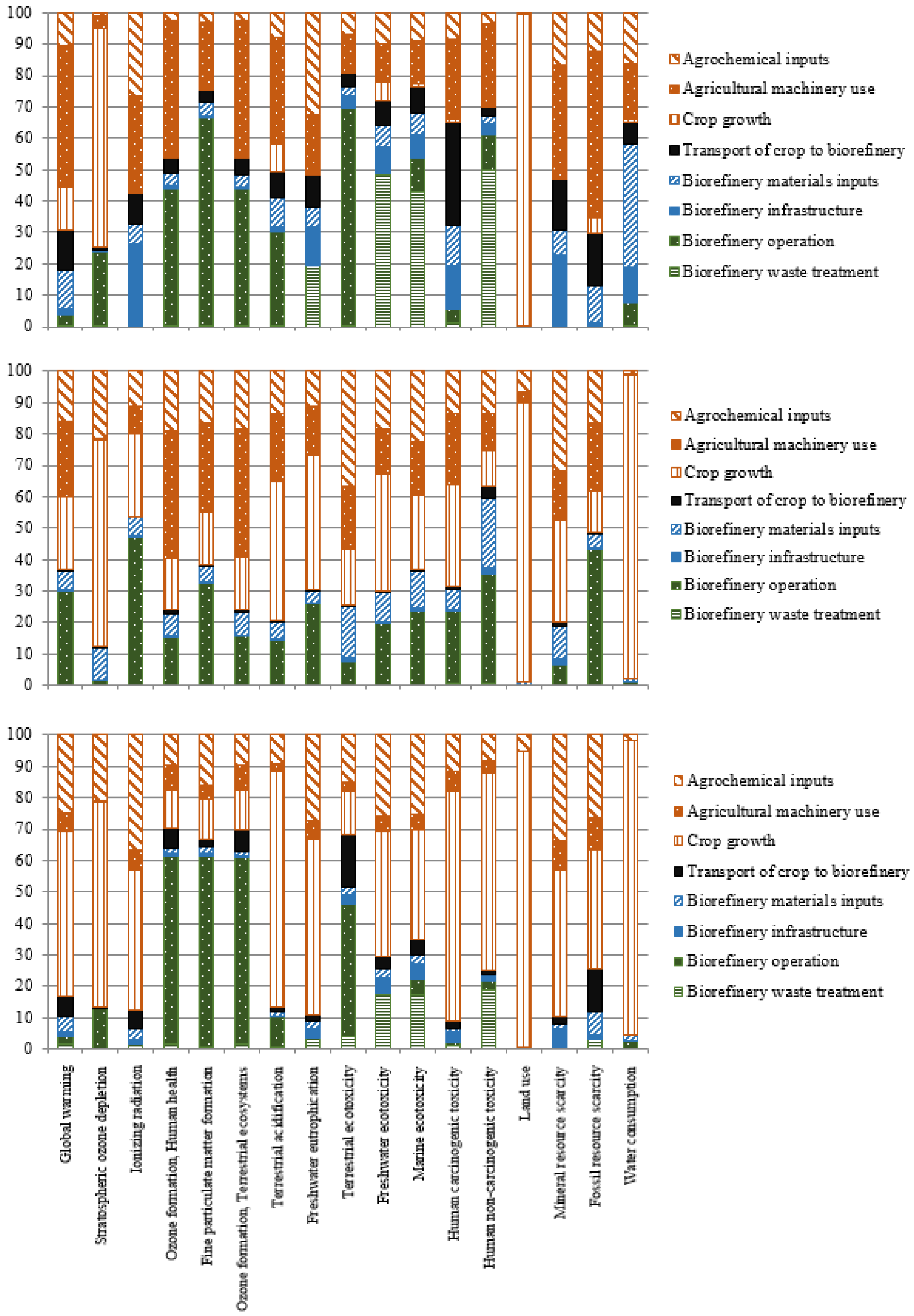

Figure 6 Contributions of main life cycle stages to the different categories of environmental impacts for ethanol produced from (unit: %) top- agave in Australia (5-year old plants with no surplus electricity generated from bagasse); middle- corn in US; and bottom- sugarcane in Brazil.

3.4 Economic assessment

The cash flow for 1G ethanol production from 3y (Table 5) and 5y (Table 6) agave were projected and net present value (NPV) calculated using a 5% discount rate. The agave feedstock production costs were US$0.94/L (70% of total costs) and US$0.46/L (53% of total costs), for 3y and 5y agave, respectively. Assuming 1G ethanol processing costs of US$0.40/L **(**Hofstrand, 2018**)**, the overall production costs were US$1.34/L and US$0.86/L for ethanol produced from 3y and 5y agave, respectively. Hence, agave feedstock costs in Australia are lower than the US$3/L agave feedstock costs estimated for Mexico, which is 6 times higher than the current price of ethanol (US$0.50/L) (Nunez et al., 2011).

Table 5 Cash flow projection and net present value calculation for 3-year agave (1G)

Production stage ($/ha)	**Year**			
	1st	**2nd**	**3rd**	**Total**
Land preparation	3,373	0	0	**3,373**
Planting	3,692	0	0	**3,692**
Maintenance (chemical application, and pruning) (Including diesel use for tractors and the cost of labour)	1,313	1,313	1,313	**3,938**
Harvesting	0	0	2,635	**2,635**
Total cost for each year	8,377	1,313	3,948	**13,637**
Average production cost ($/ha/y)	**4,546**			
Ethanol processing stage				
Cost of processing 4854 L/ha/year x 3y @ $0.4/L	0	0	5825	**5,825**
Total production and processing costs per year	8,377	1,313	9,772	**19,462**
Average total production and processing costs ($/ha/y)	6,487			
Average total production and processing costs ($/L)	**1.34**			
Revenue from ethanol 4854 L/ha/year x 3y @ $0.5/L	0	0	14,562	
Total cost of production and processing costs	8,377	1,313	9,772	
Cash flow	-8,377	-1,313	4,790	

Cumulative cash flow	-8,377	-9,690	-4,900	
Net Present Value (NPV) @5% discount rate	**-$5,031**			

Table 6 Cash flow projection and net present value calculation for 5-year agave (1G)

Production stage ($/ha)	**Year**					
	1st	**2nd**	**3rd**	**4th**	**5th**	**Total**
Land preparation	3,373	0	0	0	0	**3,373**
Planting	3,692	0	0	0	0	**3,692**
Maintenance (chemical application, and pruning) (Including diesel use for tractors and the cost of labour)	959	959	959	959	959	**4,794**
Harvesting	0	0	0	0	3,444	**3,444**
Total cost for each year	8,023	959	959	959	4,402	**15,302**
Average production cost ($/ha/y)	**3,060**					
Ethanol processing stage						
Cost of processing 6673 L/ha/year x 5 y @ $0.4/L	0	0	0	0	13,346	**13,346**
Total production and processing costs per year	8,023	959	959	959	17,748	**28,648**
Average total production and processing costs ($/ha/y)	5,730					
Average total production and processing costs ($/L)	**0.86**					
Revenue from ethanol 6673 L/ha/y x 5 y @ $0.5/L	0	0	0	0	16,683	
Total cost of production and processing costs	8,023	959	959	959	17,748	
Cash flow	-8,023	-959	-959	-959	-1,066	
Cumulative cashflow	-8,023	-8,982	-9,941	-10,900	-11,965	
Net Present Value (NPV) @5% discount rate	**-$10,963**					

The sensitivity analysis of the NPV with changes in ethanol price (Figure 7) shows that the NPV will only become positive at US$1.5/L and US$1/L ethanol price for 3y and

5y agave, respectively. This means that 1G ethanol produced from agave is currently not profitable until the ethanol price is >US$1/L (double the current price of US$0.50/L), consistent with the conclusion by Subedi et al. (2017). This suggests that government support is necessary for agave-based ethanol, as is true for most biofuels in production.

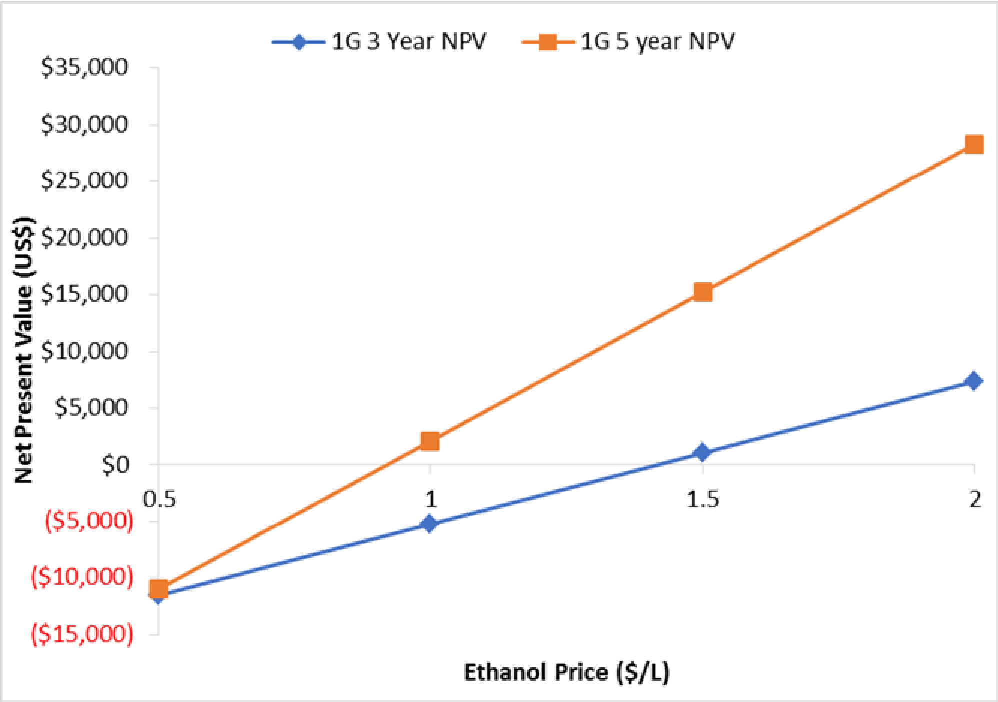

Figure 7 Net present value (US$) projection for 1G ethanol produced from 3y and 5y agave

3.5 Limitations and further research needs

The Water Consumption values calculated here include only blue water (i.e., freshwater from lakes, dams, rivers and aquifers) but not green water (i.e., soil moisture from precipitation), which was not covered by current LCI databases (Salmoral et al., 2018) Water Consumption would be even higher for sugarcane in comparison to agave and corn if green water is taken into account. This is attributed to the higher average rainfall in the sugarcane growing regions in Brazil (1407 mm; Marin et al., 2015) than in the

Corn Belt in the US (940 mm; Ort et al., 2014) and the agave field at Kalamia Estate in Australia (947 mm; Australian Government Bureau of Meteorology, 2018).

Our study is based on agave yield measured at a field experiment in Queensland on land that was previously used for agricultural purposes. Future studies should explore the effects of potential yield variation across Australia, particularly in areas that receive less rainfall, on the life cycle impacts.

Another limitation is the uncertainty in 2G ethanol conversion efficiency as the technology is still not mature. This is also the reason why economic analysis was not performed for the 1G+2G production options. Therefore, the analysis on 2G ethanol production in our study can be improved when better data is available in the future. Direct land use change emission is a key parameter that is not considered in our study due to lack of data. However, there is potential for carbon sequestration when agave is grown in arid regions and this should be accounted for in future LCA studies. Experimental research is needed to determine the scale of this potential.

4. Conclusion

This is the first comprehensive LCA and economic analysis of ethanol produced from a 5-year agave field experiment. Overall, agave performs better than current 1G biofuel crops such as corn and sugarcane in water-related environmental impact categories and produces competitive ethanol yields (L/ha/y). Although its Land Use impact is high, agave can be grown in unfavourable conditions which do not support food crop production. Overall, our results show that agave is a promising feedstock for biofuel production in arid regions that should be supported in the context of the WEFE nexus.

We present the first comprehensive LCA and economic analysis of ethanol produced from agave grown in Australia using data collected from a 5-year field experiment in Queensland. Our analysis shows that an ethanol yield of 7414 L/ha/y (6673 from the juice using 1st generation ethanol technology and 741 from the bagasse using 2nd generation technology) is achievable with agave plants harvested at 5-years old. The economic analysis suggests that 1G ethanol production from agave is not commercially viable without government support, as with most biofuels in production.

The LCA results suggest that ethanol production using 1G technology only performs better than 1G+2G technologies mainly because of the significant surplus electricity generated from the 1G only production option. In addition, agave performs much better than current 1G biofuel crops such as corn and sugarcane in water-related impacts, including Freshwater Eutrophication, Freshwater Ecotoxicity, Marine Ecotoxicity and Water Consumption. The life cycle fossil energy use (Fossil Resource Scarcity) for agave is significantly lower than corn and only slightly higher than sugarcane. Agave is not a major food crop and therefore will not have a direct impact on the global or local food market. Although its Land Use impact, measured by land occupied per unit ethanol output, is higher than corn and sugarcane, it can potentially be grown on arid land that is not suitable for food crops. Therefore, competition with food production for land can largely be avoided. The environmental performance of agave is also favourable when compared with corn and sugarcane.

Overall, our analysis suggests that agave is a highly beneficial feedstock for biofuel production in arid regions such as Australia that should be supported in the context of the WEFE nexus.

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6. Appendix: Electronic Supplementary Data

Supplementary data of this work can be found in online version of the paper.

Table S1. Different production scenarios considered

Table S2. Agricultural inputs and their active ingredients for agave plants harvested at 3 and 5 years old based on information from the field trial at Kalamia Estate

Table S3. Agricultural machinery activities (number of times used) based on information from the field trial at Kalamia Estate

Table S4. Biorefinery material inputs (kg/kg ethanol produced) based on the sugarcane ethanol production dataset in Ecoinvent database

Table S5. Estimated biorefinery energy inputs and outputs (per kg ethanol produced) based on the modelling work of Dias et al. (2012 and 2013) on sugarcane ethanol production

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8. Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. ‡These authors contributed equally.

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