



A Review on Techno-Economic Analysis and Life- Cycle Assessment of Second Generation Bioethanol Production via Biochemical Processes

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ABSTRACT Cellulosic ethanol production via biochemical pathways is currently going through its premature stages of technology development and commercialization. Techno-economic analysis (TEA) should be carried out with each case to support the commercialization of advanced ethanol production. Life-cycle assessment (LCA) is a powerful tool for distinguishing and examining environmental impacts, energy consumption, and economic viability of various pathways for lignocellulosic ethanol as well as figuring out hot spots for future innovation. TEA along with LCA provide a comprehensive basis for making decisions. This review summarizes and compares the production cost and environmental impacts of ethanol production from different lignocelluloses by diverse biochemical conversion techniques as well as provides an information source for forthcoming studies correlating economic and environmental issues of bioenergy production. It was figured out that forestry biomass, agro-wastes, and energy crops all represent potential feedstocks for cost-effective ethanol production. Other factors such as feedstock accessibility, system efficiency and integration, co-product revenue significantly affect ethanol production cost as well as the minimum ethanol selling price (MESP). MESP tends to reduce under increased economies of scale and increase under rising feedstock costs. A review of studies showed a wide variance between final and predicted results due to large uncertainties. Cellulosic (second generation) ethanol production and utilization are believed to generate lower greenhouse gas (GHG) emissions compared to those from first-generation ethanol. Local environmental impacts differ from case to case. Residual organic substances, land and fertilizer use determination, and biodiversity are the

main factors related to impacts of ethanol produced from agricultural wastes, energy crops, and forestry biomass, respectively.

Keywords: biomass, lignocellulosic, ethanol, techno-economic, life-cycle, cellulosic, pretreatment.

INTRODUCTION

A comprehensive review of TEA and LCA is quite rare and outdated. Gnansounou and Dauriat (2011) reviewed TEA of lignocellulosic ethanol via biochemical and thermochemical pathways. Brown (2015) introduced a review of thermochemical cellulosic biofuels pathways. Patel et al. (2016) presented an overview of TEA and LCA of thermochemical processes. This review was conducted in view of the lack updated papers on trends in TEA and LCA of cellulosic ethanol production via biochemical pathway. The purpose of this paper is to review the minimum ethanol selling price (MESP) and the related state-of-the-art. The minimum ethanol selling price is a fundamental variable in the economic feasibility of cellulosic ethanol production from numerous biofuel pathways. Twenty three research studies from 1999 to 2018 were examined to observe the trend of MESP vis-à-vis economies of scale and feedstock cost. GHG emissions and local environmental impacts during cellulosic ethanol production and utilization were also investigated to provide a broader understanding about long-term life-cycle of those technologies. A review of sensitivity analyses is out of scope in this study.

Currently, fossil fuels contribute around 80% of globally total energy consumption (400 billion GJ per year) and these premium fuels are projected to disappear within the next 50 years (Saidur et al. 2011). Utilization of fossil fuels is causing hazardous phenomena such as global warming, urban smog, acid rain, and Arctic sea ice decline (Saidur et al. 2011; Koh and Hoi 2003). The energy sector shares about 68% of world anthropogenic GHG emissions in which CO₂ comprises approximately 90% (IEA 2017). World average CO₂ emission is about 5 tonnes per inhabitant in which the USA, Canada, and Australia together accounts for approximately 16 tonnes of CO₂ per inhabitant. In order to achieve targets under the “Paris Agreement” (COP21) for stabilizing the global warming below 2°C above the pre-industrial level, the global median value must reduce to around 1.5 tonnes of CO₂ per inhabitant by 2050 (Balibar 2017).

Energy security and environmental issues are forcing humanity to shift from fossil fuels to alternatives which are renewable and friendly to the environment such as solar, wind, hydro, geothermal, wave, tidal, ocean thermal, and biomass energies (Muradov and Veziroğlu 2011). Among of these renewable energies, biomass is the most accessible and affordable due to its local availability and easy convertibility (Demirbas 2004). The organic materials which are derived from living species (animals and plants) is termed biomass (Fasina 2008). The energy stored in biomass materials essentially originated from solar energy which is a renewable energy resource, therefore biomass can be classified as a carbon neutral source of energy (Saidur et al. 2011). The carbohydrates stored in biomass are considered as bioenergy and when the plants die or biomass is combusted after being transformed into fuels such as solid fuels (for e.g. charcoal), liquid fuels (for e.g. ethanol), and gaseous fuels (for e.g. methane), the energy contained in these carbohydrates is released and carbon dioxide is discharged back into the atmosphere (Saidur et al. 2011). The process of storing carbohydrates into the biomass (natural process) takes a longer time compared to anthropogenic processes. If the quantity of new biomass generated by nature and human is equal to the biomass amount utilized for human purposes there will be no net addition of carbon dioxide released to the atmosphere; in this case biomass is recognized as a carbon sink. The process of growing and burning biomass is now understood as carbon neutral or net zero carbon footprint (Pande and Bhaskarwar 2012; Saidur et al. 2011). Utilization of biomass as an energy source can generate many advantages for society, such as: (1) oxygen discharge and carbon dioxide absorption when growing plants; (2) reduction of the dependence on fossil fuels; (3) reduction of the dependence on imported fuels; (4) exclusively sustainable carbon-based option; (5)

minimizing sulfur emission, (6) additional subsidiary value of agricultural crops; (7) additional jobs in rural areas, (8) diverse forms of converted energy; and (9) reduction of landfills used when utilizing waste materials (Vassilev et al. 2010). However there are also many drawbacks relating to biomass utilization, including: (1) low bulk density; (2) low calorific value; (3) high moisture content; (4) heterogeneity; (5) scattering of biomass sources; (6) seasonal variation of biomass production; (7) logistics related problems; and (8) high investment cost (Vassilev et al. 2010).

Bioethanol is one of the most important renewable fuels which can partially alternate fossil-extracted fuels. Bioethanol with its high octane value (108) can (knocking????) early ignition of internal combustion engines leading to high anti-knock value (Balat 2007). In spite of the low energy content compared to gasoline, high oxygen content of bioethanol produces a cleaner combustion and thus reduces emission of toxic substances (Krylova et al. 2008). Substitute petrol by bioethanol can decrease CO₂ emission up to 80%, hence a better environmental benefit for next generations (Aditiya et al. 2016). Recently, thanks to the utilization of biofuels including bioethanol and biodiesel, California State reported that its 2016 GHG emissions dropped below 1990 levels for the first time since emissions reached the peak in 2004. According to The California Air Resources Board (CARB), carbon emission dropped 13% statewide since 2004 and emission per capita reduced 23% from 2001 to 2016. The transportation sector contributed the largest proportion of emissions in California in 2016 (36%). CARB noted that in 2016, approximately 1.5 billion gallons of biofuels (10% of total transportation fuel) were consumed by California’s vehicles due to the state’s Low Carbon Fuel Standard. These low-carbon fuels, primarily comprising ethanol, biodiesel and renewable diesel, avoided 14 million tonnes of carbon dioxide during 2016 (Voegele 2018).

From 2007 to 2012 bioethanol production rose from 50 billion liters to exceed 100 billion liters in which Brazil and US contributed around 62-80% with corn and sugarcane as the major feedstocks (Kang et al. 2014; Sarkar et al. 2012). The “Aggressive Biofuel Growth” scenario aims to replace 10% of gasoline production with biofuels by 2010, 15% by 2015, and 20% by 2020 throughout most of the world (Chen and Qiu 2010). The agreement implemented by Policy Energy Act (PEA) followed by the Energy Independence and Security Act (EISA) aims to reach around 136.28 billion liters of bioethanol by the year of 2022 (Limayem and Ricke 2012). The US ethanol production was 41.26 billion liters and 48.52 billion liters in 2009 and 2010 respectively and increased to approximate 59 billion liters in 2017 (1.02 million barrels per day) (Limayem and Ricke 2012; EIA 2017). Since December 2010 Canada has a federal mandate requiring 5% of the national gasoline pool to be ethanol and 2% renewable content in diesel fuel. Many provinces have equivalent or higher provincial mandates including Ontario (5%), Saskatchewan (7.5%), and Manitoba (8.5%) (GAIN 2016). Canada ethanol production was around 1.75 – 1.80 billion liters in 2016 and remained constant in 2017 (STATISTA 2018; GAIN 2016). In 2017, Canada contributed around 1.7% of the world ethanol production. To meet the blend mandate Canada requires over 2 billion liters of fuel grade ethanol (GAIN 2016). Table 1 shows ethanol production by top 5 countries and the rest of the world (Renewable Fuels Association, 2018).). In 2017, the USA accounted for 58.5% of the world ethanol production followed by Brazil (26%), Europe (5.2%), and China (3.2%).

Table 1. World fuel ethanol production by country or region (million gallons)

Country	2007	2008	2009	2010	2011	2012	2013	2014	2015	2017
USA	6,521	9,309	10,938	13,298	13,948	13,300	13,300	14,300	14,806	15,800
Brazil	5,019	6,472	6,578	6,922	5,573	5,577	6,267	6,190	7,093	7,060
Europe	570	734	1,040	1,209	1,168	1,179	1,371	1,445	1,387	1,415
China	486	502	542	542	555	555	696	635	813	875
Canada	211	238	291	357	462	449	523	510	436	450

Rest of World	315	389	914	985	698	752	1,272	1,490	1,147	1,450
WORLD	13,123	17,644	20,303	23,311	22,404	21,812	23,429	24,570	25,682	27,050

Source: Renewable Fuels Association (2018).

Lignocellulosic biomass is the sole sustainable resource which is abundant and cost-effective to supply large-scale bioethanol production (Wyman and Yang 2017). Lynd et al. (2017) found that biomass price which was of \$60-80/dry tonne could be approximate in unit energy cost to petroleum at around \$21-29/barrel. Langholtz et al. (2016) estimated that 1.5 billion tonnes was the minimum biomass amount which could be supplied at a cost of less than \$60/tonne and hence sufficient to generate on the order of 100 billion gallons of gasoline equivalent. Lignocellulosic materials such as woody and forestry biomass, agricultural residues and energy crops were estimated to be around 200 billion tons annually (Zhang 2008). In 2050, bioenergy was predicted to supply 200-500 EJ/year in comparison to 600-1000 EJ/year of world primary energy demand (Chen et al. 2017b). Bioethanol manufactured from lignocellulosic biomass (second generation bioethanol) can address the issues related to the disadvantages of first generation bioethanol (ethanol derived from sugary and starchy biomass) such as the high price of raw materials, food crisis, and undesirable GHG reduction level (Mohapatra et al. 2017).

Second generation ethanol production via biochemical pathway includes the following main processes: hydrolysis of hemicellulose, hydrolysis of cellulose, fermentation, separation of lignin residue, recovery and concentration of ethanol, and wastewater handling (Galbe and Zacchi 2007). There are 4 types of process configurations for producing lignocellulosic ethanol regarding the conditions of saccharification/fermentation: Separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous hydrolysis and co-fermentation (SSCF), and consolidated processing (CBP) (Parisutham et al. 2014). Table 2 summarizes some pros and cons of each ethanol production configuration.

Table 2. Alternative Ethanol Production Configurations (Parisutham et al. 2014; Chen and Fu 2016)

Separate Hydrolysis & Fermentation (SHF)	Simultaneous Saccharification & Fermentation (SSF)	Simultaneous Saccharification & Co-fermentation (SScF)	Consolidated Bioprocessing (CBP)
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<ul style="list-style-type: none"> ● Separate hydrolysis and fermentation process with the focus in taking full advantages of each process. ● The hydrolysate is entered into the 1st reactor to get the glucose component fermented. The ethanol is distilled afterwards, then the remaining of the hydrolysate is flowed into the 2nd reactor to get the xylose components fermented. Similarly, the ethanol is removed through distillation process afterwards. <p>Drawback:</p> <ul style="list-style-type: none"> - The inhibition formation after hydrolysis, which reduces the hydrolysis rate and hence gives a lower and slower ethanol production. - Chance of contamination due to long period process. 	<ul style="list-style-type: none"> ● Allows the enzymes to perform hydrolysis to release the sugars and immediately ferment those sugars into ethanol without any separation process in between. ● Prevents the reduction of the monomers formed after hydrolysis process. ● Results higher ethanol yield since the hydrolysis inhibitions are solved by fermentation process, which makes this approach is desirable. ● Lesser employment of enzymes. ● Faster production period. ● Less number and volume of reactors needed. ● Lower cost required since both sugars releasing and sugars fermenting processes are commenced simultaneously. ● Reduce the number of reactors required ● Difference in optimum temperature conditions of enzyme for hydrolysis and fermentation 	<ul style="list-style-type: none"> ● Mixing different fermenting microorganisms. ● Allows the mixed-culture microbes to commence the continuous process without sugars separation, to use various materials as the substrate, and no involvement of sterilization. ● Effective in ethanol production from corn stover, MSW, and sugarcane bagasse. 	<ul style="list-style-type: none"> ● In ethanol production from cellulosic materials, this approach performs self-cellulase production, hydrolysis of the substrates, and fermentation of hexose, as well as pentose sugars within the same reactor utilizing the ability of certain microorganisms to perform these tasks. In comparison with SHF, CBP offers better benefits including: <ul style="list-style-type: none"> - Lower production cost due to lesser steps required and no additional purchase of enzymes. - Better efficiency of conversion. - Lesser energy required to run the production. <p>Drawback:</p> <ul style="list-style-type: none"> - Uncommon for wild type of microorganisms to work on CBP method. - Low rate of ethanol conversion process. - Considerably low ethanol yield. <p>Efforts:</p> <ul style="list-style-type: none"> - Modification of employed microorganisms genetically.
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Currently, most of the second-generation bioethanol is in the early phases of commercialization or pilot production phase. In 2018, only 1.1% of U.S. ethanol production was from lignocellulosic materials, with majority (96%) originating from corn starch (Figure 1). Cellulosic ethanol production is facing significant challenges including feedstock access, supply chain infrastructure development, and price parity with the petroleum industry (UNCTAD 2016). In order to accelerate the deployment of cellulosic ethanol, Davison et al. (2015) suggested a comprehensive set of important issues which must be overcome including: (1) huge supply chain for scaling up the industry to reach the global goals; (2) massive market demand for co-products; (3) feedstock storage and logistics regarding the low density and decomposition; (4) land-use and other

sustainable issues; (5) improvements in yield and convertibility; (6) robust, easily convertible lignocellulosic feedstock with minimal pretreatment; (7) predictable agronomic feedstock improvements for yield and sustainability; (8) ability to control the soil microbial communities to improve feedstock traits; (9) economically stable bioconversions able to handle feedstock variability; (10) new tools to rapidly and rationally genetically engineer new microbial isolates with unique complex capabilities; (11) rational reproducible control of energy fluxes and carbon balance in microbes; (12) cellular redesign to overcome fermentation product inhibition while maintaining yield and rate; (13) expanded compatible biotechnology processes to produce co-products along with fuels.

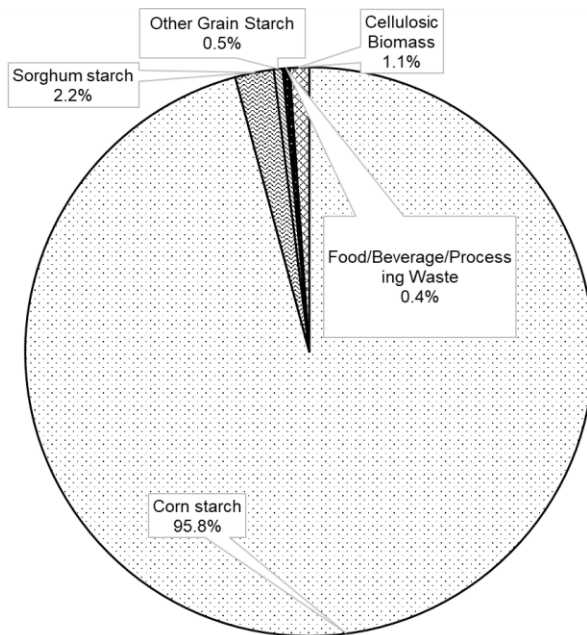


Figure 1. U.S. Ethanol production capacity by feedstock type (Source: 2018 RFA Ethanol Industry Outlook)

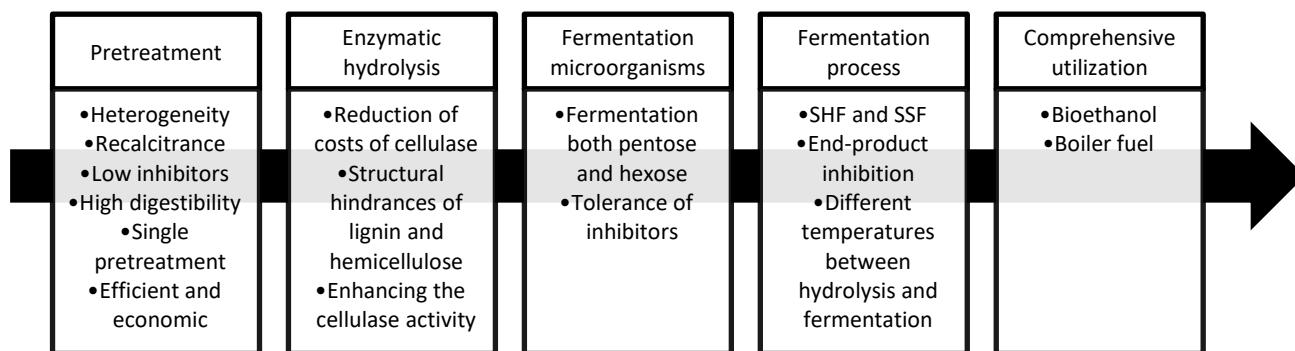


Figure 2. Summary of challenges related to second generation ethanol production via biochemical pathway (Chen and Fu 2016).

Figure 2 shows the barriers preventing a competitive production and hence commercialization of cellulosic ethanol processing via biochemical conversion. The major drawbacks are harsh pretreatment, cellulase cost, vigorous industrial strains, efficient enzymatic hydrolysis and fermentation, and related high total project investment. Since the cost of feedstock accessibility is

minimized and the efficiency and scale of systems are improved, or innovation in other advanced process is explored, cellulosic ethanol cost reduction can be achieved (Chen and Fu 2016).

TECHNO-ECONOMIC ANALYSIS OF ETHANOL PRODUCTION VIA BIOCHEMICAL PATHWAYS

Ethanol production cost is affected by both technical and economic factors, including but not limited to bioconversion technology and its efficiency, type and price of feedstock and logistic costs, cost of waste treatment, government subsidy programs, and revenue from selling of co-products (Brown et al. 2014; Roy 2014). Gubicza et al. (2016) introduced a simple calculation of ethanol production cost as the following:

$$\text{Ethanol production cost} = \frac{\text{Annualized capital cost} + \text{Annual operating cost} - \text{Annual coproduct income}}{\text{Annual ethanol production}} \quad (1)$$

The most important factors which need to be focused on to reduce the ethanol production cost are: (1) high ethanol yields; (2) high ethanol concentration during fermentation; (3) low feedstock cost; (4) large enough plant capacity; (5) process integration for a lower capital cost and energy demand; (6) maximized co-products such as heat, electricity and (7) lignin derived biochemicals (Galbe and Zacchi 2007; Galbe et al. 2007). Advanced pretreatment techniques, improved enzymatic hydrolysis with less expensive and more effective enzymes, as well as enhanced fermentation systems represent dominant research challenges in the competitiveness of lignocellulosic-derived ethanol with first generation ethanol (Galbe et al. 2007). There are many pretreatment technologies which have been introduced by scholar and industrial communities (Table 3). Each of them has pros and cons which result in wide variability in pretreatment cost as well as ethanol production cost. Table 4 and 5 represent the direct fixed capital cost and principal operating cost of several common pretreatment methods. At the moment, there is an absence of a proven comprehensive large scale model to guide the industry and encourage investors to invest in cellulosic ethanol production. The following sections will summarize some recent studies about the TEA of second generation ethanol production in the US as well as other countries.

Table 3. Classification of biomass pretreatment technologies (Sarkar et al. 2012; Balat 2011; Baskar et al. 2012; Faraco 2013; Zabed et al. 2016; Chen et al. 2017a; Zheng et al. 2009; Bajpai 2016; Travaini et al. 2016; Limayem and Ricke 2012; Singh et al. 2014)

Physical pretreatment	Mechanical Comminution. Drying and Concentration. Granulometric Separation. High – Energy Radiation (Microwave Oven & Electron Beam Irradiation). Pyrolysis
Chemical pretreatment	Acid Alkaline Ionic Liquid (IL) Organosolv Ozonolysis Oxidative Delignification Sulfite
Physicochemical pretreatment	Steam Explosion Liquid Hot Water (LHW) Ammonia Fiber Expansion (AFEX); Ammonia Fiber Extrusion (FIBEX) Ammonia Recycled Percolation (ARP) and Soaking in Aqueous Ammonia.
Biological pretreatment	Ligninolytic Abilities of Fungi Enzymatic Pretreatment

Cellulose solvent – based lignocellulose	Cellulose Solvent – and Organic Solvent – Based Lignocellulose Fractionation Aqueous N – Methylmorpholine – N – Oxide Urea / Sodium Hydroxide N, N – Dimethylacetamide (DMAc) / LiCl
Combination	Alkaline + Dilute Acid (ALK – DA) Alkaline + Ionic Liquid (ALK – IL) Dilute Acid + Steam Explosion (DA – SExp.) Supercritical CO ₂ + Steam Explosion (SCCO ₂ – SExp.) Organosolv + Biological (Bio – Organosolv) Biological + Dilute Acid (Bio – DA) Biological + Steam Explosion (Bio – SExp.) Microwave – Assisted Alkaline (MW – ALK) Dilute Acid + Microwave (DA – MW) Ionic Liquid + Ultrasonic (IL – UL)

Table 4. Direct fixed capital costs of some various pretreatment techniques.

Method	Corn stover (Eggeman and Elander 2005)	Switchgrass (Tao et al. 2011)
	\$/ (m ³ .day)	\$/ (m ³ .day)
Liquid hot water (LHW)	2,250	10,000
Dilute acid (DA)	12,500	22,500
Soaking in aqueous solution		22,500
Lime	11,150	28,500
Ammonia fiber explosion (AFEX)	12,850	15,500
Steam explosion with SO ₂		17,500

Table 5. Principal operating cost for pretreatment methods (Conde-Mejia et al. 2012).

Pretreatment	Principal operating cost
Steam explosion (SE)	Energy consumption
Liquid hot water (LHW)	Energy consumption
Dilute sulfuric acid hydrolysis (DA)	Energy consumption and acid cost
Ammonia fiber explosion (AFEX)	Energy consumption and ammonia cost
Alkali extraction with Ca(OH) ₂ (LIME)	Energy consumption and lime recovery and lime cost
Organosolvent using ethanol-water mixture as solvent (OS)	Energy consumption and solvent recovery cost

Table 6 summarizes some of recent studies on TEA of second ethanol manufacturing. All the adjusted data based on US\$ of 2018 using annual US PP index (all commodities) are presented in the Appendix in order to consider inflation (Sanchez and Gomez 2014). Currency-related information is provided in USD. Results of some studies mentioned in Table 6 are discussed in more detail in the upcoming sections. .

Table 6. Publication considered in reviewing the techno-economic analysis of ethanol production from different types of lignocellulosic feedstock via a variety of biochemical pathways (original data)

Published year and	Lct.	Feedstock	Ethanol capacity	Feedstock cost	TCI	MESP	Note	Ref.
			MM L/y	\$/L	\$/MM	\$/L		

Analysis cost year									
1999 (1997\$)	US	Hardwood chips	197.6	0.10	234.0	0.38	DA pretreatment, SSCF process, on-site enzyme production, electricity co-product, 1997\$, Near-term, base-case	NREL 1999 Wooley et al. (1999b)	
			222.6	0.10	205.0	0.31	Near-term, best of industry		
			235.5	0.10	169.0	0.25	Futuristic case, Year of 2000		
			273.3	0.10	156.0	0.22	Futuristic case, Year of 2005		
			331.2	0.10	159.0	0.20	Futuristic case, Year of 2015		
2000 (1999\$)	US	Corn stover	94.6	0.13	131.6	0.40	DA prehydrolysis + SSCF + on-site enzyme production, electricity co-product, 1999\$	McAloon et al. (2000)	
2002 (2000\$)	US	Corn stover	262.3	0.09	197.4	0.28	DA prehydrolysis + SSCF + on-site enzyme production, electricity co-product, 8406 hr/y, 2000\$	NREL 2002 Aden et al. (2002)	
2009 (2006\$)	US	Switchgrass	504.6	0.15	603.8	0.45	Base case: NREL 2002, DA pretreatment, SSF process, two column distillation, evaporation and suspended sludge digester	Mark et al. (2009)	
			697.7	0.11	359.1	0.19	Mature technology case: AFEX pretreatment, CBP process, IHOSR (intermediate heat pump with optimal side stream return) distillation, attached film digester, Rankine power cycle.		
			697.7	0.11	532.6	0.20	Mature technology case: AFEX pretreatment, CBP process, IHOSR (intermediate heat pump with optimal side stream return) distillation, attached film digester, Gas turbine combined cycle (GTCC)		
2010 (2007\$)	US	Corn stover	202.2	0.29	376.0	0.90	NREL 2002 design (2007\$), Dilute-acid pretreatment (base case)	Kazi et al. (2010)	
			192.1	0.30	389.0	0.95	Dilute-acid pretreatment (high solids)		
			147.7	0.39	361.0	1.17	Hot water pretreatment		
			174.8	0.33	386.0	0.97	AFEX pretreatment		
			124.2	0.47	391.0	1.16	Two-stage DA pretreatment		
			179.4	0.32	434.0	0.94	On-site enzyme production		
			210.1	0.28	386.0	0.97	Separate C5 and C6 fermentation		
			203.9	0.28	501.0	0.99	Pervaporation-distillation		
2011 (2007\$)	US	Corn stover	230.9	0.20	422.5	0.57	DA prehydrolysis + SHF + on-site enzyme production, electricity co-product, 2007\$	NREL 2011 Humbird et al. (2011)	
2012 (2007\$)	US	Corn stover	185.5			0.68	NREL 2011, base (control) case	Tao et al. (2012)	
			242.3			0.56	Deacetylation + mechanical refining		
2013 (2007\$)	US	Corn stover	125.3	0.36	388.9	0.88	Hot water pretreatment, on-site enzyme production, SHF process, organic acids/steam/electricity co-products, 2007\$ <i>S. cerevisiae</i>	Meyer et al. (2013)	
			167.3	0.27	381.9	1.47	<i>S. cerevisiae</i> + xylose isomerase		
			179.4	0.25	410.5	0.69	<i>P. stipitis</i>		
			179.4	0.25	370.7	0.66	Recombinant <i>S. cerevisiae</i>		
			137.0	0.33	392.8	0.89	<i>F. oxysporum</i>		
			131.0	0.35	329.4	0.81	<i>F. oxysporum</i> in CBP		
2013 (2008\$)	Mexico	Wheat straw & agro-residue	193.6	0.29	389.5	0.99	DA pretreatment, SHF process, purchased enzyme, 2008\$, 80% polysaccharides content	Sanchez et al. (2013)	
2014 (2012\$)	US	Corn grain & Corn stover	180.6			0.99	Stand-alone Gen 2 plant	Ou et al. (2014)	
			48.5			1.38	Co-located Gen 1+Gen 2 plants with SGM ratio of 0.4:1		
			92.4			1.13	Co-located Gen 1+Gen 2 plants with SGM ratio of 0.6:1		

			136.3			1.02	Co-located Gen 1+Gen 2 plants with SGM ratio of 0.8:1	
			180.6			0.96	Co-located Gen 1+Gen 2 plants with SGM ratio of 1:1	
2014 (2013\$)	US	Poplar wood	204.0	0.34	722.0	0.81	Organosolv pretreatment, SHF process, electricity/furfural/acetic acid co-product, 2013\$	Kautto et al. (2014)
2015 (2014\$)	Colombia	Wood residue (Pinus patula bark)	44.5	0.82	42.2	1.08	Non-integrated scenario	Moncada et al. (2016)
			60.8	0.60	65.7	0.79	Full energy integration based on the composites curves relating to hot and cold streams	
			84.3	0.44	81.3	0.57	Full-integrated scenario plus a cogeneration scheme to produce heat and electricity to cover remaining biorefinery supply	
2016 (2012\$)	Sweden	Sawdust and shavings	29.0	0.32	205.1	0.77	Sulfur dioxide impregnation + steam pretreatment, SSF process, purchased enzyme, pellet/steam/electricity/biogas co-product, 2012\$	Frankó et al. (2016)
		Debarked fuel logs	21.4	0.57	195.9	0.94		
		Fuel logs	20.4	0.57	206.3	0.97		
		Early thinnings	18.1	0.62	206.6	1.01		
		Tops and branches	15.8	0.67	209.3	1.06		
		Hog fuel	6.3	1.35	209.4	1.52		
		Debarked pulpwood	20.3	0.65	195.9	0.99		
2016 (2012\$)	US	Sugarcane bagasse	83.0	0.15	196.8	0.63	DA pretreatment, Liquefaction + SSaF process, heat/electricity production from solid stillage, biogas and sludge; experimental parameters	Gubicza et al. (2016)
			83.0	0.15	180.7	0.58	Base case	
2016 (2014\$)	Brazil	Sugarcane bagasse and trash	36.3		31.9	0.17	First-gen mill with intra-mill pretreatment, 2014\$ (1)	Losordo et al. (2016)
			36.3		33.4	0.29	First-gen mill with intra-mill pretreatment & cane trash collection (1b)	
			68.4		107.4	0.30	First-gen mill with pretreatment after the mill & cane trash collection (2b)	
2017 (2007\$)	US	Miscanthus x giganteus (perennial grass)	231.0	0.25	464.4	0.65	NREL 2011, 8410 hr/y, feedstock price \$0.08/kg, 2007\$	Boakye-Boaten et al. (2017)
			231.0	0.31	464.4	0.71	Feedstock price \$0.10/kg	
2017 (2012\$)	US	Corn stover			25.6	0.55	NREL 2011, AFEX pretreatment, 2012\$	Stoklosa et al. (2017)
					9.8	0.72	AHP pretreatment, no alkali recovery	
					14.9	0.67	AHP pretreatment, Re-causticization (NaOH recovery) from pre-extraction	
					17.2	0.60	AHP pretreatment, Re-causticization (NaOH recovery) from pre-extraction and AHP	
2017 (2010\$)	Sweden	Spruce chips	55.2	0.25		0.74	Steam pretreatment, SSF, integrated enzyme production (B+)	Olofsson et al. (2017)
			54.6	0.26		0.76	Purchased enzyme case (Off-Site)	
2017 (2015\$)	Canada	Wheat straw	208.0	0.19	200.0	1.00	NREL 2002, 2015\$	Mupondwa et al. (2017)
2018 (2010\$)	Brazil	Empty fruit bunches of palm	57.2	0.13	226.6	0.82	NREL 2011, Only-fuel, biogas, surplus electricity, 2010\$	Vaskan et al. (2018)
			30.7	0.28	204.1	0.67	Feed-fuel, C5 syrup, biogas co-products	
2018 (2016\$)	South Africa	Sugarcane	213.7		372.0	0.84	1G ethanol, 2016\$	Petersen et al. (2018)
		Bagasse and trash	61.5		250.0	0.38	2G-Int-SM	
		Bagasse	196.4		400.0	0.66	2G-standA	

		Sugarcane and bagasse	299.8		425.0	0.63	1G-2G	
2018 (2016\$)	Iran	Wheat straw	20.0	0.28	21.5	1.23	Steam explosion pretreatment, SSCF process, steam/electricity by-product, 2016\$	Hasanly et al. (2018)
2018 (2007\$)	US	Corn stover	230.9	0.20	624.5	0.27	NREL 2011 By-product lignin undergoes a hydrothermal liquefaction (HTL) process Lignin-derived biochemicals: catechol, phenol, cresols, acetic acid, formic acid, furfural, acetaldehyde Remaining is combusted for heat and power	Bbosa et al. (2018)

U.S. cases: Wooley et al. (1999b) from National Renewable Energy Laboratory (NREL), U.S. Department of Energy investigated a complete process design and economics of yellow poplar hardwood chips-based ethanol plant. The process used co-current dilute sulfuric acid prehydrolysis of the lignocellulose with simultaneous enzymatic saccharification of the surviving cellulose and co-fermentation of the derived glucose and xylose to ethanol. Elements of the process included feedstock handling-storage-size reduction, pretreatment and detoxification, simultaneous saccharification and co-fermentation (SSCF), on-site enzyme production, product recovery, anaerobic and aerobic digestion wastewater treatment, ethanol storage and steam/electricity generation. Plant life was set at 20 years and the economics was evaluated based on 15% internal rate of return (IRR) and 100% equity financing. Plant capacity was set at 198 million liters of ethanol per year. Five cases were examined comprising Near-Term Base-Case; Near-Term-Best of Industry Improvements from Base-Case; Year 2005, 2010, 2015 Improvements from Best of Industry. The techno-economic performance of these cases was respectively, 257.4 L/tonne ethanol yield, 197.6 MM L/year plant capacity, \$234 million capital investment, \$0.38/L production cost (case 1); 287.7 L/tonne ethanol yield, 222.6 MM L/year plant capacity, \$205 MM capital investment, \$0.31/L production cost (case 2); 306.6 L/tonne ethanol yield, 235.5 MM L/year plant capacity, \$169 MM capital investment, \$0.25/L production cost (case 3); 355.8 L/tonne ethanol yield, 273.3 MM L/year plant capacity, \$156 MM capital investment, \$0.22/L production cost (case 4); 374.8 L/tonne ethanol yield, 331.2 MM L/year plant capacity, \$159 MM capital investment, \$0.20/L production cost (case 5) (US\$ of 1997). The last case was calculated based on the assumption of 20% carbohydrates increment due to biotechnology enhancement.

McAloon et al. (2000) from NREL introduced the same process design with Wooley et al. (1999b) except corn stover was used as feedstock in this study. Plant size was set at 94.6 million annual liters of fuel ethanol and the year 1999 was chosen as the basis for costs. Total capital investment was \$136.1 MM and the production cost was found to be \$0.396/L. Excess electricity as a co-product can be sold to the grid at \$0.04/kWh and therefore added an important credit of \$0.029/L of fuel ethanol.

Aden et al. (2002) from NREL followed the same framework of previous NREL studies with some significant changes: (1) corn stover was the feedstock, (2) plant capacity was 262.3 MM L/year, (3) a purchased cellulose enzyme production is conducted. The economic evaluation was based on 10% IRR and 100% equity financing. The total project investment was \$197.4 MM and the MESP was estimated at \$0.283/L (US\$ of 2000).

Kazi et al. (2010) conducted a techno-economic comparison of different process technologies for biochemical ethanol production from corn stover. Eight scenarios were assigned to develop the process models using ASPEN Plus™ Process Simulator including: (1) Dilute-acid pretreatment (base case), (2) Dilute-acid pretreatment (high solids), (3) 2-stage dilute-acid pretreatment, (4) Hot water pretreatment, (5) AFEX pretreatment, (6) Pervaporation-distillation, (7) Separate C5 and C6

fermentation, (8) On-site enzyme production. Pinch technology was used to optimize the process heat requirement, and the mass and energy flow rates from simulations were used to size process equipment. The base case was modified from the process design in the NREL 2002 report (Aden et al. 2002). The enzyme was assumed to be sourced externally except the case of on-site enzyme production. Equipment costs and chemical prices were indexed to 2007 dollars. Dilute acid pretreatment was found to produce ethanol with lowest MESP (\$0.90/L) with the TCI of 202.2 MM L/y. Separate C5 and C6 fermentation was found to give the highest yield (210.1 MM L/y) with the MESP of around \$0.97/L.

Humbird et al. (2011) built a research upon the previous issues from Wooley et al. (1999a) and Aden et al. (2002) in which they displayed NREL’s latest visualized ethanol production via biochemical process, contemporary research progress in the areas of conversion as well as the product recovery optimizations and newest knowledge of the ethanol plant’s back end (separation, wastewater, and utilities). This research aimed to generate a new baseline or “zero-point” techno-economic benchmark from which process possible choices and advancements could be examined by others in the public realm. The process was set up as separate hydrolysis and fermentation (SHF) which was different from the simultaneous saccharification and co-fermentation (SSCF) process developed by Aden et al. (2002). Ethanol yield was estimated around 329.6 L/dry tonne feedstock and the plant capacity reached about 230.9 MM L/year. The production cost was found to be \$0.57/L. The techno-economic evaluation was conducted based on 10% IRR, 40% equity financing and indexed to US\$ of 2007. The total capital investment was \$422.5 million. Figure 3 and 4 indicate the elemental contributions of total installed cost (TIC) and total manufacturing cost (TMC). It can be seen clearly that feedstock (35%), capital return on investment and tax (27%), and fixed cost and capital depreciation (18%) contribute the majority in production cost followed by the enzyme production (9%) and pretreatment (4%) cost.

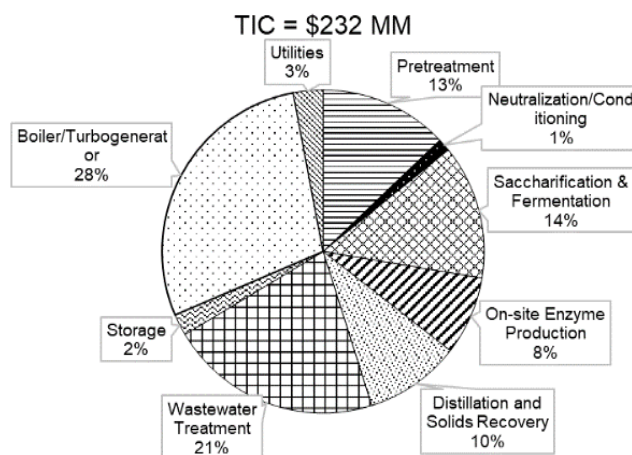


Figure 3. Contribution of different element in TIC (plotted from data of Humbird et al. (2011))

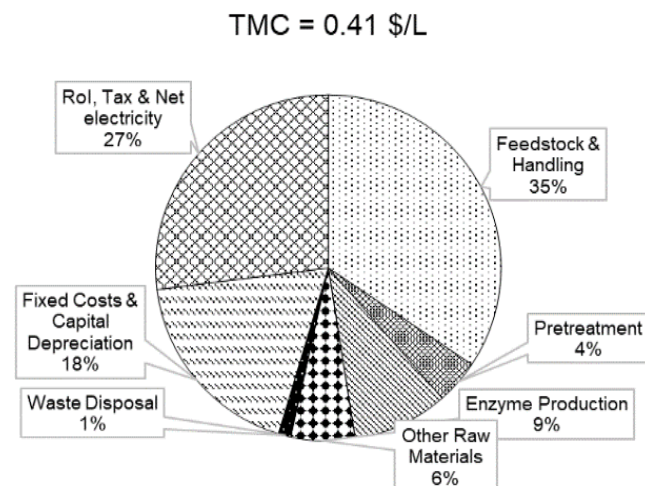


Figure 4. Contribution of different element in TMC (plotted from data of Humbird et al. (2011))

Tao et al. (2012) carried out a TEA based on NREL’s AspenPlus model in which the options of deacetylation, mechanical refining, and a solids washing step were introduced. The MESP of ethanol manufactured from two corn stover categories under base (control) and modified process case. The feedstock consumption was set at 2000 MT/day. The base-case ethanol production capacity was found to be 185.5 and 159 MM L/year in 34M95 and 33B51 corn stover, respectively.

Simultaneous deacetylation and mechanical refining increased the ethanol production capacity from 185.5 to 242.3 MM L/year for 34M95 corn stover, and from 159 to 212 MM L/year for 33B51 corn stover. As compared to the base case (\$0.77/L), the MESP was found to be \$0.56/L in the deacetylation and disk refining combination scenarios which was quite approximate with the result from 2011 NREL design case (\$0.57/L).

Miscanthus x giganteus, a perennial grass, was examined by Boakye-Boaten et al. (2017) to understand its techno-economic performance during ethanol production via biochemical conversion process. The process design was adapted from the NREL 2011 design (Humbird et al. 2011). The TCI for the entire project was \$464.4 MM for a 231 MM L/year ethanol production capacity yielding a TCI per annual liters of \$2.01/L. In the contributions of the different areas of the proposed plant to the total cost, feedstock costs comprised 39-44% of the total cost (sum of total cost of equipment, variable operating cost, and fixed operating cost) for the feedstock cost ranging from 0.08-0.10 \$/kg. Enzyme cost and wastewater treatment cost stood at second class which comprises 15.7 and 15.6% of the overall cost, respectively. The MESP was \$0.65/L and \$0.71/L at feedstock pricing of \$0.08/kg and \$0.10/kg, respectively. The prices were indexed to US\$ of 2007, the equity financing was 40% and the IRR was 10%.

In 2018, Bbosa et al. (2018) introduced a system based on the work of Humbird et al. (2011) with the integration of hydrothermal liquefaction process (HTL). The HTL was developed by Pacific Northwest National Laboratory (PNNL). By-product lignin from corn stover fermentation was processed by HTL and 80% of the input was used to produce lignin-derived chemicals such as acetic acid, acetaldehyde, phenol, formic acid, catechol, cresols, and furfural. The remaining was used to combust in boiler for co-generation. The MESP was found around \$0.27/L with \$624.5 MM of TCI. The economy of scale reached around 230.9 MM L/year. Factors affected MESP the most were figured out as TCI, internal rate of return (IRR), feedstock price, as well as the prices of acetic acid, cresols and catechol.

Other cases: Ethanol production from empty fruit bunches (EFB) as a waste of palm oil extraction process in Brazil was investigated by Vaskan et al. (2018). Two biorefinery scenarios were examined: the EFB 'feed-fuel' (EFB FF) scenario which produced ethanol and syrup from C5 sugars as a cattle feed supplement, and the EFB 'only fuel' (EFB OF) scenario which produced only ethanol as the main product. The process design was based on the one from Humbird et al. (2011). The pretreatment techniques used for EFB OF and EFB FF scenarios were dilute acid (DA) and liquid hot water (LHW), respectively. After pretreatment the treated stream was processed by SHF method. The ethanol production costs of EFB OF and EFB FF scenarios were \$1038/t (\approx \$0.82/L) and \$849/t (\approx \$0.67/L), respectively, as compared to considered market price \$760/t (\approx \$0.60/L). The TCIs, FCs, and VCs of EFB OF and EFB FF scenarios were found to be around \$226.6 MM and \$204.1 MM, \$8.3 MM/y and \$7.9 MM/y, \$8.9 MM/y and \$3.9 MM/y, respectively.

Olofsson et al. (2017) from Sweden modelled two integrated enzyme process designs for ethanol from spruce chips and compared it to an off-site (purchasing enzyme) case. The MESP was from €0.568/L (\approx \$0.74/L) to €0.622/L (\approx \$0.81/L) to the integrated case, as compared to €0.581/L (\approx \$0.76/L) for the off-site case (2010 exchange rate, 1 EUR \approx 1.3 USD). It was found that factor other than enzyme cost such as selling prices of co-products affected the MESP and economics of the systems studied.

In a Canadian study, Mupondwa et al. (2017) examined the large scale commercial production of wheat straw-derived ethanol in the Canadian Prairies. Eleven locations in the province of Saskatchewan were investigated and Yorkton was found to be the most suitable location in terms of tonnes per radius kilometer per year. The economies of scale suggested optimal plant size of approximate 250 million L annum⁻¹. MESP and IRR were estimated at \$1/L and 7% respectively to generate a positive NPV. Smaller size plants were found to be more adversely affected by

feedstock cost compared to larger size plants. For high ethanol prices of 1.3-1.7 \$/L, all plant capacities generated positive NPV within a feedstock cost range of 35-70 \$/t and regardless of total capital investment. High MESP compared to gasoline price in this research suggested that subsidy from government and R&D such as consolidated bioprocessing (CBP) and wheat straw supply chain should be enhanced to make cellulosic ethanol more competitive in Canada.

Petersen et al. (2018) from South Africa examined an economic analysis for ethanol and electricity production using integration strategies of 1st and 2nd generation technologies with sugarcane and sugarcane bagasse as feedstocks. He found that cellulosic ethanol could be cost-effective when integrating it into existing facilities such as sugar mills or autonomous distilleries (i.e., 1st generation ethanol plant) and converting on-site residues to biofuels, heat and electricity. This manner is different to a standalone 2nd generation strategy which requires centralized facilities where lignocellulose must be imported to produce biofuels and electricity. Such integration was proved to decrease the MESP of 2nd generation ethanol. The minimum MESP was found in second-generation ethanol production integrated into an existing, upgraded sugar mill (\$0.38/L) followed by those of combined first- and second-generation ethanol production (\$0.63/L) and second-generation standalone ethanol production (\$0.66/L).

Figure 5 shows the relationship between ethanol production capacity and MESP among the 23 studies. It can be seen that increasing plant capacity can reduce production cost. Most of the trends in Figure 5 show the inversely proportional relationship between plant capacity and MESP. The majority of studies show high production cost compared to the reference price (\$0.49/L), the five year average of anhydrous ethanol prices paid to the producers (USD of 2018) (CEPEA 2018). The cases which generated competitive MESP were switchgrass (607.7 and 504.6 MM L/y) (Mark et al. 2009), hardwood chips (222.6-331.2 MM L/y) (Wooley et al. 1999b), corn stover (262.3 MM L/y) (Aden et al. 2002), corn stover (230.9 MM L/y) (Bbosa et al. 2018), sugarcane bagasse and trash (61.5 MM L/y) (Petersen et al. 2018), and sugarcane, bagasse, and trash (36.3-68.4 MM L/y) (Losordo et al. 2016). It can be concluded that all kinds of lignocellulosic family represent potential feedstock candidates for the production of bioethanol competitively (Woody biomass: hardwood chips, agricultural residues: corn stover, sugarcane bagasse, switchgrass). Factors which significantly affect the production cost are feedstock availability, system efficiency, revenue from selling co-products, and the integration of second-generation plant into conventional bioethanol production process or existing process (sugar mill). Figure 6 represents the relationship between feedstock cost and MESP. The figure shows that the MESP tend to increase with an increase in feedstock cost in all studies. Most raw material contributions to total production cost range between 40% and 60%. This is consistent with anecdotal experience within the biofuels industry (Sanchez and Gomez 2014). Due to the re-valorization of residues, the cost of feedstock is increasing in the current market (Sanchez and Gomez 2014).

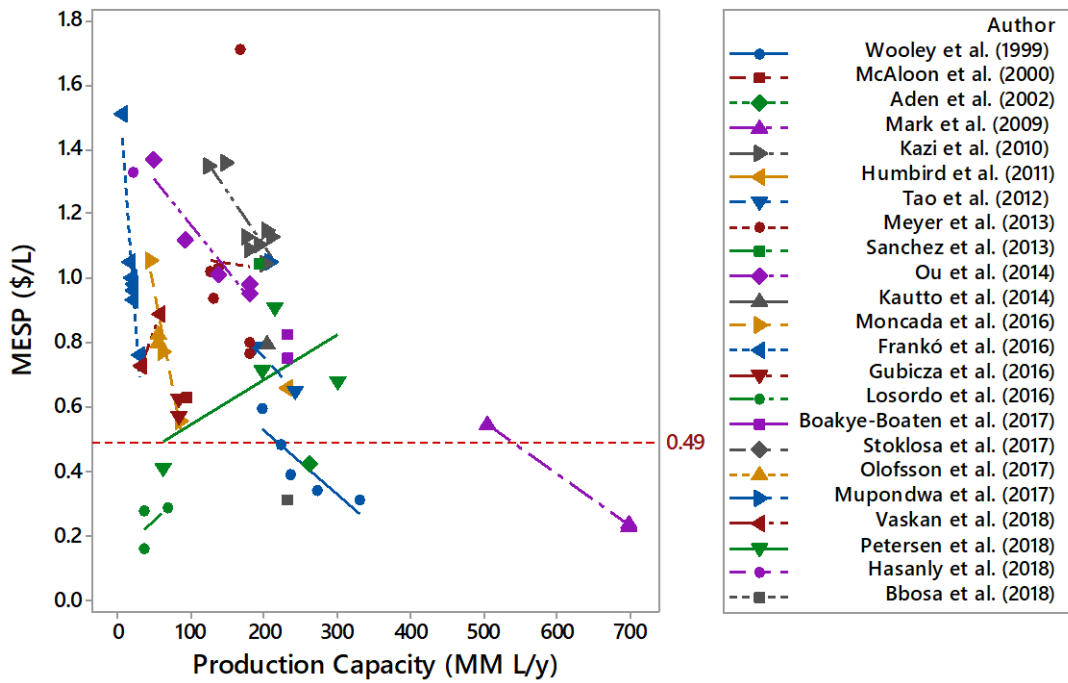


Figure 5. Ethanol production capacity versus minimum ethanol selling price (detailed data given in the appendix)

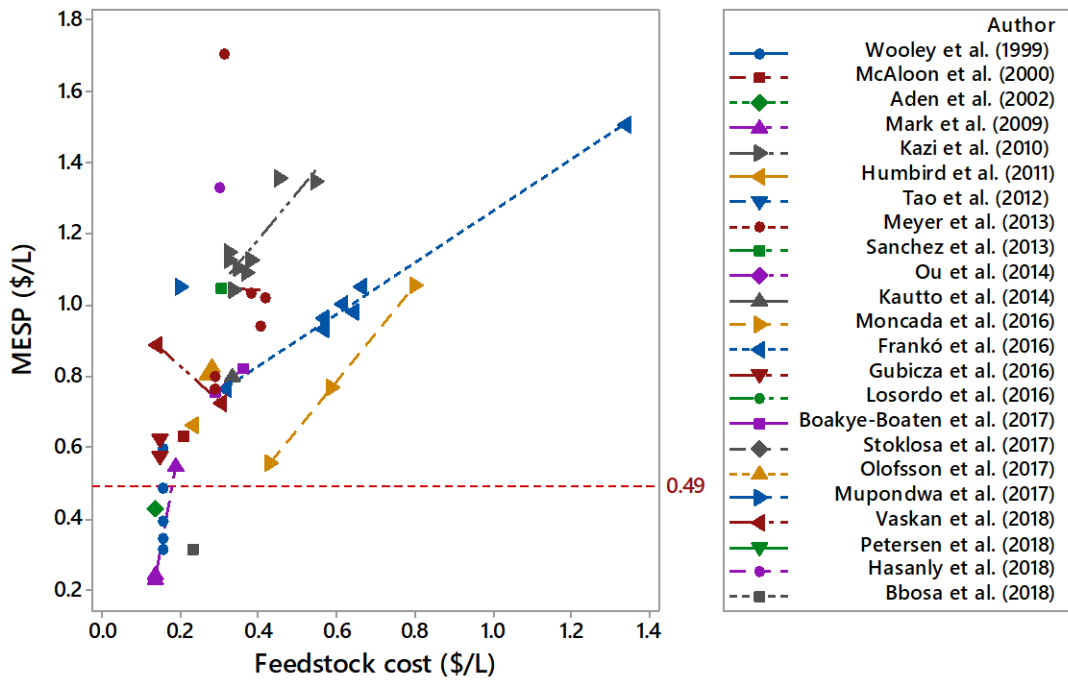


Figure 6. Cost of feedstock regarding to cost of 1 liter of ethanol produced (detailed data given in the appendix).

LIFE-CYCLE ASSESSMENT OF LIGNOCELLULOSIC ETHANOL PRODUCTION VIA BIOCHEMICAL PATHWAYS

Life cycle assessment is a popular and powerful tool for investigating emissions as well as evaluating the influence of a product from cradle to grave all over its life cycle (Oliveira and Rosentrater 2017). Fueling vehicles with a nationally manufactured, lignocellulose-derived fuel has the capability to become a promising route toward enhancing environmental quality and sustainability of the nations' quality and transportation sectors (Spatari et al. 2005). Lignocellulosic ethanol can improve energy security and contribute significantly to abating GHG emissions. Reduction in GHG emission is reported to be dependent on feedstock, conversion technology, utilization of co-products and allocation methods (Roy et al. 2012). The largest environmental impacts when utilizing lignocellulose in biorefinery systems occur in the four impact classifications: (1) fossil fuel use; (2) respiratory effects; (3) land use; and (4) carcinogenics (Uihlein and Schebek 2009). González-García et al. (2009) considered the following parameters in their analysis: acidification, eutrophication, photochemical oxidants formation, global warming, and fossil fuels extraction; while abiotic resource depletion, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity were added in the examination from González-García et al. (2010a). Compared to thermochemical pathways, biochemical conversion is considered to have more favorable environmental performance. In the short term, it had better environmental performance such as GHG emission and energy consumption while still consuming more water resources (Mu et al. 2010). Biochemical conversion of lignocellulosic ethanol was able to achieve around 50% GHG emission reduction in comparison with utilizing non-renewable fuel. Ethanol via biochemical pathway could save around 1.13 MJ/L fossil fuel consumption but on the other hand it released chemicals such as phosphorous and nitrogen into the atmosphere resulting the eutrophication, acidification, and photochemical smog (Limayem and Ricke 2012; González-García et al. 2010b). Ethanol from agricultural wastes was cost-effective only under conditions under which its production in sufficient quantity together with facilities to convert it within an appropriate distance were satisfied. The willingness of farmers (participation rate) to produce energy crops and/or remove a part of residues from their field was also a sustainability factor (González-García et al. 2010b). Best management practices and above-ground residue harvest rates need to be conducted to minimize the amount of agro-wastes left on the soil to maintain soil organic carbon (SOC), minimize erosion and protect soil quality and productivity (Cherubini and Ulgiati 2010). Chang et al. (2017) examined the LCA of bioethanol production from rice straw, napier grass and eucalyptus. Rice straw was found to require largest amount of fuel, labor and energy input followed by eucalyptus and napier grass. However, eucalyptus had the highest CO₂ equivalent emissions followed by rice straw and napier grass. It might be due to the fact that eucalyptus was 5-7 years old and the emissions during planting/weeding/tending processes were high. In this study, napier grass was found to be the most suitable feedstock for ethanol production. Switchgrass- and corn stover-derived E85 ethanol fuels were found to produce 57% and 65% GHG emissions lower than low-sulfur reformulated gasoline. Emissions associated with E85 vehicles majorly came from the blend proportion of gasoline fuel (production and combustion), fertilizer and herbicide application during crop growth, agricultural and transportation activities. Corn stover was proved to produce slightly less GHG emissions (N₂O, CH₄, CO₂), CO, NO_x, and nonmethane organic compounds (NMOC) emissions than switchgrass did. In term of SO_x and Particulate Matters, both cellulosic derived fuels generated the same amount in well-to-tank analysis. The smaller impacts of corn stover ethanol fuel production and utilization was primarily related to the shared emissions with grain production. E85 automobiles were found to be able to achieve up to 70% lower GHG emissions across the life cycle compared to low-sulfur reformulated gasoline (RFG) automobiles (Spatari et al. 2005). Exact calculation of GHG savings on biorefinery systems is complicated. Local and climate conditions affect basic assumptions such as land use change effects and therefore produce large uncertainty. Other parameters which influence the final

results are type of feedstocks, conversion routes, type of fuels used, end-use applications, and methodological assumptions (Cherubini and Ulgiati 2010). Table 7 summarizes some recent LCA case studies about the production and utilization of agrowaste-, woody- and energy crop-derived bioethanol.

Table 7. Some recent studies on life-cycle assessment of cellulosic ethanol production.

Feedstock	GHGs Emission and other impacts	References
Rice straw	Functional Unit (FU): 1000 L bioethanol at 99.7 vol% Climate change: 1488.7-1501.9 [kg CO ₂ eq] Terrestrial acidification: 21.8-51.9 [kg CO ₂ eq] Freshwater eutrophication: 0.8 [kg P eq] Marine eutrophication: 11.3-12.9 [kg N eq] Human toxicity: 31.3-94.8 [kg 1,4-DB eq] Photochemical oxidant formation: 5.3-17.9 [kg NMVOC] Particulate matter formation: 5.1-6.1 [kg PM10 eq] Terrestrial ecotoxicity: 0.4-371.8 [kg 1,4-DB eq] Freshwater ecotoxicity: 1.2-60.1 [kg 1,4-DB eq] Fossil depletion: 113.4-692.8 [kg oil eq] CO ₂ : 214.4-2270.8 [kg] CO: 3.4-4.0 [kg] CH ₄ : 46.1-46.2 [kg] NO _x : 4.3-15.0 [kg] N ₂ O: 0.8-0.9 [kg] NH ₃ : 7.5-7.7 [kg] SO ₂ : 1.0-24.6 [kg] NMVOC: 183.9-285.2 [$\times 10^{-3}$ kg] Particulates: 478.4-1590.3 [$\times 10^{-3}$ kg] Heavy metals: 39.6-46.5 [$\times 10^{-3}$ kg] Herbicides/Pesticides: 4.8 [kg] Nitrate: 45.3-50.2 [kg] Phosphorous: 3.9-4.1 [kg]	Rathnayake et al. (2018)
Empty Fruit Bunches (EFB)	FU: 1 t of EFB, results below were for EFB FF and EFB OF scenarios respectively: Climate change: 26.6 and 79.3 [kg CO ₂ eq] Fossil depletion: 9.1 and 23.0 [kg 1,4-DB eq] Human toxicity: 296.7 and 416.5 [kg 1,4-DB eq] Freshwater toxicity: 0.256 and 0.250 [kg 1,4-DB eq] Freshwater eutrophication: 0.028 and 0.027 [kg 1,4-DB eq]	Vaskan et al. (2018)
Cattle Manure	FU: 1000 kg of cattle manure Climate change: 1.51E+00 [kg CO ₂ eq] Ozone depletion: -7.77E-07 [kg CFC-11 eq] Human toxicity: 1.72E+01 [kg 1,4-DB eq] Photochemical oxidant formation: 1.04E-02 [kg NMVOC] Particulate matter formation: -2.04E-02 [kg PM10 eq] Ionizing radiation: 3.35E-01 [kg U ₂₃₅ eq] Terrestrial acidification: -2.11E-01 [kg SO ₂ eq] Freshwater eutrophication: 7.72E-04 [kg P eq] Marine ecotoxicity: 1.37E+01 [kg 1,4-DB eq] Agricultural land occupation: 1.11E-02 [m ² a] Urban land occupation: 3.22E-03 [m ² a] Natural land transformation: 2.42E-04 [m ²] Water depletion: 5.07E-02 [m ³] Metal depletion: 2.03E-02 [kg Fe eq] Fossil depletion: 1.06E+00 [kg oil eq]	de Azevedo et al. (2017)
Rice straw	FU: 1 MJ transportation fuel GHG emission: -Dilute Acid (DA) pretreatment: 292 [kg CO ₂ eq] -Steam Explosion (SE) pretreatment: 288 [kg CO ₂ eq]	Soam et al. (2016)

	<p>The cradle-to-grave life cycle GHG emissions of E100 using DA and SE were 20 and 8 [g CO₂ eq] respectively, corresponding to 77 and 89% GHG emission reductions as compared to the gasoline.</p> <p>Net energy use: 0.19 MJ</p> <p>Net energy balance: 14.9 [MJ/L] (DA) and 16.3 [MJ/L] (SE)</p>	
Pulp and Paper Sludge	<p>FU: 1 MJ of bioethanol produced</p> <p>Abiotic depletion: 3.72E-7 [kg Sb_{eq}]</p> <p>Abiotic depletion (fossil fuel): 7.83E-1 [MJ]</p> <p>Global warming (GWP100a): 7.17E-2 [kg CO₂ eq]</p> <p>Ozone layer depletion: 1.72E-8 [kg CFC-11 eq]</p> <p>Human toxicity: 4.92E-2 [kg 1,4-DB eq]</p> <p>Freshwater aquatic ecotox.: 2.68E-2 [kg 1,4-DB eq]</p> <p>Marine aquatic ecotoxicity: 6.62E+1 [kg 1,4-DB eq]</p> <p>Terrestrial ecotoxicity: 3.36E-4 [kg 1,4-DB eq]</p> <p>Photochemical oxidation: 4.12E-5 [kg C₂H₄ eq]</p> <p>Acidification: 5.75E-4 [kg SO₂ eq]</p> <p>Eutrophication: 8.56E-4 [kg PO₄³⁻ eq]</p>	Sebastião et al. (2016)
Corn stover	<p>FU: 1 km driving distance in a midsize car (cradle-to-grave), results were of E10 and E85 respectively.</p> <p>Global warming: 0.265 and 0.147 [kg CO₂ eq]</p> <p>Stratospheric ozone depletion: 2.96E-8 [kg R11 eq]</p> <p>Acidification: 9.29E-3 [m² UES]</p> <p>Terrestrial eutrophication: 5.86E-3 [m² UES]</p> <p>Aquatic eutrophication: 1.25E-4 [kg NO₃ eq]</p> <p>Photochemical oxidant formation: 4.31E-8 [person*ppm*h]</p>	Daylan and Ciliz (2016)
Spruce	<p>FU: 1 MJ ethanol using LHV</p> <p>A scenario: pretreated liquid fraction, B scenario: pretreated liquid fraction and molasses.</p> <p>Global warming ISO method: 2.13 (A) and 2.03 (B) MJ</p> <p>Global warming RED method: 1.65 (A) and 1.60 (B) MJ</p>	Olofsson et al. (2015)
Wheat Straw and Forestry Residue (Spruce Softwood)	<p>FU: 1 MJ ethanol, results below were of Straw and Forestry Residue, respectively</p> <p>ISO method:</p> <p style="padding-left: 20px;">GHG performance: 41.36 nad 13.24 [g CO₂ eq]</p> <p style="padding-left: 20px;">Energy balance: 0.024 and -0.710 [MJ]</p> <p>RED method:</p> <p style="padding-left: 20px;">GHG performance: 15.46 nad 14.86 [g CO₂ eq]</p> <p style="padding-left: 20px;">Energy balance: 0.196 and 0.202 [MJ]</p>	Karlsson et al. (2014)
Tropical banagrass (Pennisetum purpureum)	<p>FU: 10000 MJ of energy</p> <p>Results below were of case 1 (green processing with co-product), case 2 (gree processing without co-product), and case 3 (dry processing without co-product) respectively.</p> <p>Net energy value: 1800, 2400 and 2800 [MJ]</p> <p>Net energy ratio: 1.2, 1.3 and 1.4</p> <p>GHG emissions: 144, 90.6 and 59.1 [kg CO₂ eq]</p> <p>Well-to-wheel for 1 km driving distance: 280, 260 and 250 [g CO₂ eq]</p>	Mochizuki et al. (2014)
Corn Stover	<p>CO₂, biogenic: 21.01 [kg/GGE]</p> <p>SO₂: 11.31 [g/GGE]</p> <p>NO₂: 13.47 [g/GGE]</p> <p>Water: 8.19 [gal/GGE]</p> <p>Below is for with and without electricity credits</p> <p>GHG emission: 4.3 and 6.5 [kg CO₂ eq./GGE]</p> <p>Fossil fuel energy input: 43 and 69 [MJ/GGE]</p> <p>Energy return on investment: 2.7:1 and 1.5:1</p> <p>Net energy value: 87 and 51 [MJ/GGE]</p>	Tao et al. (2014)
Wheat straw	<p>FU: 1 km in a Flexible-fuel vehicle</p> <p>Results below were of Dilute Acid, Steam Explosion with acid catalyst, Steam Explosion without acid catalyst, Liquid Hot Water, and Wet Oxidation, respectively.</p> <p>Abiotic resources Depletion Potential: 1.19E-03, 1.13E-03, 3.96E-04, 6.85E-04, 4.10E-04 [kg Sb eq]</p>	Wang et al. (2013)

	Global Warming Potential 100 yr horizon: 0.264, 0.212, 0.134, 0.156, 0.166 [kg CO ₂ eq] Acidification Potential: 2.18E-03, 1.68E-03, 9.63E-04, 1.09E-03, 9.67E-04 [kg SO ₂ eq] Eutrophication Potential: 4.33E-04, 3.03E-04, 2.12E-04, 2.33E-04, 2.02E-04 [kg PO ₄ eq] Ozone layer Depletion Potential: 2.35E-08, 1.68E-08, 1.19E-08, 1.29E-08, 1.28E-08 [kg CFC-11 eq] Photochemical Oxidants Creation Potential: 1.27E-04, 1.07E-04, 7.09E-05, 6.88E-05, 7.14E-05 [kg C ₂ H ₄ eq] Human Toxicity Potential: 1.09E-01, 8.33E-02, 3.36E-02, 4.34E-02, 3.76E-02 [kg 1,4-DB eq] Freshwater Aquatic Ecotoxicity Potential: 4.22E-02, 3.72E-02, 2.49E-03, 7.47E-03, 5.68E-03 [kg 1,4-DB eq] Terrestrial Ecotoxicity Potential: 1.42E-03, 9.36E-04, 5.81E-06, 1.17E-04, 5.56E-05 [kg 1,4-DB eq]	
Switchgrass	FU: 1 MJ of fuel ethanol Total energy consumption: 1.3 [MJ] Well-to-wheels GHG emissions: 07 [g CO ₂ eq]	Dunn et al. (2012)

SUMMARY

Lignocellulosic materials are believed to have promising potential to supply the growing energy demand of the world. Second-generation bioethanol is a potential transportation fuel and it has shown many environmental advantages compared to conventional first-generation bioethanol. Cellulosic ethanol production via biochemical pathways has been proven to require lower capital investment and achieve better environmental performance compared to those of thermochemical pathway ethanol. Techno-economic evaluations of cellulosic ethanol production has been facing obstacles due to the lack of access to reliable data as well as economic evaluations derived from many process assumption. Cellulosic ethanol plants which are in operation may help to tackle those issues. However, since industrial data and experience are proprietary and confidential, it will perhaps take some time until the state-of-the-art is shared widely to the community. Many studies about the TEA of cellulosic ethanol production have been carried out in order to minimize the ethanol production cost and hence exploring the minimum ethanol selling price (MESP). Many ideas and innovations have been introduced including new pretreatment technologies, electricity generation from burning lignin residue and biogas, selling of biochemical by-products, integration of second-generation ethanol process with first-generation ethanol process or existing facilities such as sugar mill, etc. However, a majority of them originated from the same sources with the same assumption of feedstock and processing methodology. Empirical studies reviewed also show a wide scatter of final and forecasted results due to the uncertainties. Those uncertainties include pretreatment methods, enzyme production, concepts of efficient hydrolysis and fermentation of the recalcitrant lignocellulose. Economies of scale or ethanol production capacity is another important issue. On one hand, an increase in plant capacity leads to a reduction in production cost; on the other hand, the smaller the size of profitable plant, the lesser location dependence is achieved and therefore the overall process economy is improved. There are several influences affecting uncertainty including: (1) diversity of feasible design; (2) absence of awareness regarding the manner by which feedstock market will behave in long term in case there is a significantly high demand; (3) absence of knowledge about the ethanol market price and especially the answer for the big question about the interaction between ethanol price and gasoline price when blending percent in transportation fuel is considerable; and last but not least (4) the readiness of investors to be committed to the production of second generation bioethanol. Life cycle assessment of cellulosic ethanol production considers global issues such as global warming effect, climate change, fossil fuel consumption, and saving as well as environmental impacts such as land use and ecological changes. Most of the studies figure out that net energy value of cellulosic ethanol is positive which means cellulosic bioethanol generates more energy than energy consumed from fossil fuels used

to produce it. Assumptions used in the various studies also affect final results. These assumptions include system boundary, allocation method, valorization of co-products, method of fueling the conversion systems, and feedstock compositions. Cellulosic ethanol production and utilization are believed to generate less GHG emissions compared to those from first-generation ethanol. Local environmental impacts differ from case to case. Considering agro-wastes, impacts can be lessened by developing sustainable crop residue harvest systems which recognize the need to retain a defined percentage of organic matter onto the field for soil nourishment and maintenance of soil organic carbon. In case of energy crops, two feasible alternatives can be applied including: (1) restricted land use with intensified fertilizer utilization (intensive culture, related to soil degradation and contaminated water), and (2) larger land use with lesser fertilizer (extensive culture, related to land use impact). Forestry and woody biomass is the last case with sensitivity to biodiversity and hence must be handled with meticulous precautions.

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APPENDIX

Original and updated data (TCI: Total Capital Investment, PPI: Producer Price Index, FC: Fixed Cost, VC: Variable Cost, MESP: Minimum Ethanol Selling Price).

Author	Analysis Cost Year	PPI	ORIGINAL DATA										DATA ADJUSTED TO USD OF 2018						
			MML/y	\$/L	\$MM	\$/annual L	\$MM/y	\$/L	\$MM/y	\$/L	\$/L	\$/L	\$MM	\$/annual L	\$MM/y	\$/L	\$MM/y	\$/L	\$/L
			Capacity	Feedstock cost	TCI			FC		VC		MESP	Feedstock cost	TCI		FC		VC	
Wooley et al. (1999)	1997	127.6	197.60	0.10	234.00	1.18	7.50	0.04	25.13	0.13	0.38	0.16	367.83	1.86	11.79	0.06	39.50	0.20	0.60
Wooley et al. (1999)	1997	127.6	222.60	0.10	205.00	0.92	6.90				0.31	0.16	322.25	1.45	10.85				0.49
Wooley et al. (1999)	1997	127.6	235.50	0.10	169.00	0.72	6.20				0.25	0.16	265.66	1.13	9.75				0.39
Wooley et al. (1999)	1997	127.6	273.30	0.10	156.00	0.57	5.90				0.22	0.16	245.22	0.90	9.27				0.35
Wooley et al. (1999)	1997	127.6	331.20	0.10	159.00	0.48	5.90				0.20	0.16	249.94	0.75	9.27				0.31
McAloon et al. (2000)	1999	125.48	94.60	0.13	131.60	1.39	22.49	0.24	14.91	0.16	0.40	0.21	210.36	2.22	35.95	0.38	23.83	0.26	0.63
Aden et al. (2002)	2000	132.74	262.30	0.09	197.40	0.75	7.54	0.03	31.52	0.12	0.28	0.14	298.29	1.14	11.39	0.05	47.63	0.18	0.43
Mark et al. (2009)	2006	164.75	504.60	0.15	603.80	1.20	17.84	0.04	109.60	0.22	0.45	0.19	735.12	1.46	21.72	0.05	133.44	0.27	0.55
Mark et al. (2009)	2006	164.75	697.70	0.11	359.10	0.51	12.85	0.02	60.88	0.09	0.19	0.14	437.20	0.63	15.64	0.02	74.12	0.11	0.23
Mark et al. (2009)	2006	164.75	697.70	0.11	532.60	0.76	16.79	0.02	35.63	0.05	0.20	0.14	648.43	0.93	20.44	0.02	43.38	0.06	0.24
Kazi et al. (2010)	2007	172.66	202.20	0.29	376.00	1.86	26.20	0.13	122.40	0.61	0.90	0.34	436.80	2.16	30.44	0.15	142.19	0.71	1.05
Kazi et al. (2010)	2007	172.66	192.10	0.30	389.00	2.02	27.00	0.14	121.70	0.63	0.95	0.35	451.90	2.35	31.37	0.16	141.38	0.73	1.10
Kazi et al. (2010)	2007	172.66	147.70	0.39	361.00	2.44	25.30	0.17	112.30	0.76	1.17	0.45	419.38	2.84	29.39	0.20	130.46	0.88	1.36
Kazi et al. (2010)	2007	172.66	174.80	0.33	386.00	2.21	26.80	0.15	109.70	0.63	0.97	0.38	448.42	2.57	31.13	0.17	127.44	0.73	1.13
Kazi et al. (2010)	2007	172.66	124.20	0.47	391.00	3.15	27.20	0.22	82.50	0.66	1.16	0.55	454.23	3.66	31.60	0.26	95.84	0.77	1.35
Kazi et al. (2010)	2007	172.66	179.40	0.32	434.00	2.42	29.60	0.17	100.60	0.56	0.94	0.37	504.18	2.81	34.39	0.20	116.87	0.65	1.09
Kazi et al. (2010)	2007	172.66	210.10	0.28	386.00	1.84	26.80	0.13	142.70	0.68	0.97	0.33	448.42	2.13	31.13	0.15	165.78	0.79	1.13
Kazi et al. (2010)	2007	172.66	203.90	0.28	501.00	2.46	33.30	0.16	125.00	0.61	0.99	0.33	582.01	2.85	38.68	0.19	145.21	0.71	1.15
Humbird et al. (2011)	2007	172.66	230.90	0.20	422.50	1.83	24.10	0.10	72.70	0.31	0.57	0.23	490.82	2.13	28.00	0.12	84.46	0.36	0.66
Tao et al. (2012)	2007	172.66	185.50								0.68								0.79
Tao et al. (2012)	2007	172.66	242.30								0.56								0.65

Meyer et al. (2013)	2007	172.66	125.30	0.36	388.90	3.10	69.20	0.55	41.70	0.33	0.88	0.42	451.79	3.61	80.39	0.64	48.44	0.38	1.02
Meyer et al. (2013)	2007	172.66	167.30	0.27	381.90	2.28	69.00	0.41	176.40	1.05	1.47	0.31	443.66	2.65	80.16	0.48	204.92	1.22	1.71
Meyer et al. (2013)	2007	172.66	179.40	0.25	410.50	2.29	72.50	0.40	51.20	0.29	0.69	0.29	476.88	2.66	84.22	0.46	59.48	0.34	0.80
Meyer et al. (2013)	2007	172.66	179.40	0.25	370.70	2.07	65.90	0.37	52.60	0.29	0.66	0.29	430.64	2.40	76.56	0.43	61.11	0.34	0.77
Meyer et al. (2013)	2007	172.66	137.00	0.33	392.80	2.87	69.50	0.51	52.10	0.38	0.89	0.38	456.32	3.33	80.74	0.59	60.52	0.44	1.03
Meyer et al. (2013)	2007	172.66	131.00	0.35	329.40	2.51	58.80	0.45	47.10	0.36	0.81	0.41	382.67	2.92	68.31	0.52	54.72	0.42	0.94
Sanchez et al. (2013)	2008	189.59	193.60	0.29	389.50	2.01	40.66	0.21	151.00	0.78	0.99	0.31	412.08	2.13	43.02	0.22	159.75	0.83	1.05
Ou et al. (2014)	2012	202.16	180.60								0.99								0.98
Ou et al. (2014)	2012	202.16	48.50								1.38								1.37
Ou et al. (2014)	2012	202.16	92.40								1.13								1.12
Ou et al. (2014)	2012	202.16	136.30								1.02								1.01
Ou et al. (2014)	2012	202.16	180.60								0.96								0.95
Kautto et al. (2014)	2013	203.41	204.00	0.34	722.00	3.54	17.00	0.08	113.00	0.55	0.81	0.34	711.95	3.49	16.76	0.08	111.43	0.54	0.80
Moncada et al. (2016)	2014	205.32	44.50	0.82	42.15	0.95	7.64	0.17	110.50	2.48	1.08	0.80	41.18	0.93	7.46	0.17	107.95	2.42	1.06
Moncada et al. (2016)	2014	205.32	60.80	0.60	65.70	1.08	11.70	0.19	74.80	1.23	0.79	0.59	64.18	1.06	11.43	0.19	73.07	1.20	0.77
Moncada et al. (2016)	2014	205.32	84.30	0.44	81.28	0.96	14.50	0.17	53.40	0.63	0.57	0.43	79.40	0.94	14.17	0.17	52.17	0.62	0.56
Frankó et al. (2016)	2012	202.16	29.00	0.32	205.10	7.07	1.74	0.06	12.24	0.42	0.77	0.32	203.50	7.02	1.73	0.06	12.14	0.42	0.76
Frankó et al. (2016)	2012	202.16	21.40	0.57	195.90	9.15	1.77	0.08	14.94	0.70	0.94	0.57	194.37	9.08	1.76	0.08	14.82	0.69	0.93
Frankó et al. (2016)	2012	202.16	20.40	0.57	206.30	10.11	1.77	0.09	14.76	0.72	0.97	0.57	204.69	10.03	1.76	0.09	14.64	0.71	0.96
Frankó et al. (2016)	2012	202.16	18.10	0.62	206.60	11.41	1.77	0.10	14.18	0.78	1.01	0.62	204.99	11.33	1.76	0.10	14.07	0.77	1.00
Frankó et al. (2016)	2012	202.16	15.80	0.67	209.30	13.25	1.78	0.11	13.60	0.86	1.06	0.66	207.66	13.14	1.77	0.11	13.49	0.85	1.05
Frankó et al. (2016)	2012	202.16	6.30	1.35	209.40	33.24	1.79	0.28	11.51	1.83	1.52	1.34	207.76	32.98	1.78	0.28	11.42	1.82	1.51
Frankó et al. (2016)	2012	202.16	20.30	0.65	195.90	9.65	1.78	0.09	15.94	0.79	0.99	0.64	194.37	9.57	1.77	0.09	15.82	0.78	0.98
Gubicza et al. (2016)	2012	202.16	83.00	0.15	196.80	2.37	23.24	0.28	38.18	0.46	0.63	0.15	195.26	2.35	23.06	0.28	37.88	0.46	0.63
Gubicza et al. (2016)	2012	202.16	83.00	0.15	180.70	2.18	21.58	0.26	31.54	0.38	0.58	0.15	179.29	2.16	21.41	0.26	31.29	0.38	0.58
Losordo et al. (2016)	2014	205.32	36.30		31.90	0.88					0.17		31.16	0.86					0.17

Losordo et al. (2016)	2014	205.32	36.30		33.40	0.92					0.29		32.63	0.90					0.28
Losordo et al. (2016)	2014	205.32	68.40		107.40	1.57					0.30		104.92	1.53					0.29
Boakye-Boaten et al. (2017)	2007	172.66	231.00	0.25	464.40	2.01	11.98	0.05	78.84	0.39	0.65	0.29	539.50	2.34	13.92	0.06	91.59	0.45	0.76
Boakye-Boaten et al. (2017)	2007	172.66	231.00	0.31	464.40	2.01	11.98		91.98	0.44	0.71	0.36	539.50	2.34	13.92	0.00	106.85	0.51	0.82
Stoklosa et al. (2017)	2012	202.16			25.60						0.55		25.40						0.55
Stoklosa et al. (2017)	2012	202.16			9.76						0.72		9.68						0.71
Stoklosa et al. (2017)	2012	202.16			14.87						0.67		14.75						0.66
Stoklosa et al. (2017)	2012	202.16			17.21						0.60		17.08						0.60
Olofsson et al. (2017)	2010	184.73	55.20	0.25			27.50	0.50	19.20	0.35	0.74	0.27			29.86	0.54	20.85	0.38	0.80
Olofsson et al. (2017)	2010	184.73	54.60	0.26			25.00	0.46	23.65	0.43	0.76	0.28			27.15	0.50	25.68	0.47	0.83
Mupondwa et al. (2017)	2015	190.44	208.00	0.19	200.00	0.96	25.00	0.12	112.30	0.54	1.00	0.20	210.65	1.01	26.33	0.13	118.28	0.57	1.05
Vaskan et al. (2018)	2010	184.73	57.20	0.13	226.60	3.96	8.30	0.15	8.90	0.16	0.82	0.14	246.04	4.30	9.01	0.16	9.66	0.17	0.89
Vaskan et al. (2018)	2010	184.73	30.70	0.28	204.10	6.65	7.90	0.26	3.90	0.13	0.67	0.30	221.61	7.22	8.58	0.28	4.23	0.14	0.73
Petersen et al. (2018)	2016	185.38	213.70		372.00	1.74					0.84		402.50	1.88					0.91
Petersen et al. (2018)	2016	185.38	61.50		250.00	4.07					0.38		270.50	4.40					0.41
Petersen et al. (2018)	2016	185.38	196.40		400.00	2.04					0.66		432.80	2.20					0.71
Petersen et al. (2018)	2016	185.38	299.80		425.00	1.42					0.63		459.85	1.53					0.68
Hasanly et al. (2018)	2016	185.38	20.00	0.28	21.50	1.08	2.20	0.11	24.60	1.23	1.23	0.30	23.26	1.16	2.38	0.12	26.62	1.33	1.33
Bbosa et al. (2018)	2007	172.66	230.90	0.20	624.50	2.70	110.80	0.48	-57.60	-	0.27	0.23	725.48	3.14	128.72	0.56	-66.91	-	0.31