CHEMICAL ENGINEERING TRANSACTIONS
VOL. 34, 2013
Guest Editors: Neven Duić, Petar Sabev Varbanov

ISBN 978-88-95608-25-9; ISSN 1974-9791

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1334019

Energy Analysis of Bioethanols Produced from *Dendrocalamus latiflorus*

Chun-Han Ko[a,e], Ya-Nang Wang[a], Fang-Chih Chang*[,b], Chih-Yuan Lee[a], Wen-Hua Chen[c],Wen-Song Hwang[c],Yi-Chung Wang[d]

[a]School of Forestry and Resource Conservation, National Taiwan University, Taipei 106, Taiwan, R.O.C.
[b]Department of Environmental Engineering, National Cheng Kung University, Tainan 701, Taiwan, R.O.C.
[c]Cellulose Ethanol Program, Institute of Nuclear Energy Research, AEC, Taoyuan 325, Taiwan, R.O.C.
[d]Department of Forestry and Nature Conservation, Chinese Culture University, Taipei 111, Taiwan, R.O.C.
[e]Bioenergy Center of National Taiwan University
d90541003@ntu.edu.tw

The Ma bamboo (*Dendrocalamus latiflorus* Munro) covers 152,300 ha in Taiwan, roughly of 7.2 % the overall forest area. This study calculated the energy and mass balance of Ma bamboo as a feedstock for bioethanol production. Several processes included acidic steam explosion, alkaline steam explosion, bleached, unbleached kraft pulps, enzyme hydrolysis, and simultaneous saccharification and fermentation (SSF) for fuel ethanol production from bamboo were studied through energy consumption and energy production. The energy analysis of the compacting fermented residue was also evaluated.
Results show that the post-fermentation residues possessed high heating values. The net energy value of acidic steam explosion pulp, alkali steam explosion, kraft pulp, and bleached pulp is -1.75, 4.42, -2.71, and 2.90 MJ/kg chip. The alkali steam explosion has highest net energy value and is equivalent to 50.22 MJ/kg ethanol. The net energy gains could be achieved for the processes with greater ethanol yields: acid steam explosion and fully bleached pulps. SSF could produce 220 ML/t of starting biomass of bioethanols from acidic steam explosion pulps and 148 ML/t of starting biomass of bioethanols from alkaline steam explosion pretreatment pulps annually.

1. Introduction

Substitute for petroleum-derived fuels now has more importance such as ethanol from biomass, the most abundant renewable resources on earth – examples on sorghum from Romania (Ceclan et al., 2012) and from Austria (Theuretzbacher et al., 2012). Bamboo stands cover 152,300 hectares, roughly of 7.2 % the overall forest area in Taiwan. Bamboos are endemic in south and east Asia. Its fast growth and adaptability toward various soil and climate conditions make the bamboo a good candidate for a renewable resource. Bamboo had been conventionally used as the raw materials for producing artifacts, utensils, plywood, fiberboard, and decorated multi-layered panels in Taiwan and many Asian countries. Recently, more attention was paid for bamboo biomass as biofuel feedstock, *e. g.*, steam-exploded bamboo (Yamashita et al., 2010), simultaneous saccharification and fermentation of bamboo (Shimokawa et al., 2009), and sodium hydroxide/urea based pretreatment of bamboo (Li et al., 2010) were employed for bioethanol production. Bioethanol production from bamboo has been well studied. However, the energy analysis of bioethanols produced from bamboo is not well understood.
In past, several researchers have estimated the energy balance of the different processes converting for bioethanol production from lignocellulosic biomass (hardwood chips (Cardona Alzate and Sanchez Toro, 2006), corn stover (Luo et al., 2009), and palm (Goh and Lee, 2010)). Although, those researches show the positive net energy values to a varying extent, the energy use of compacting the fermented residue is still not considered in the energy analysis of bioethanols production from bamboo. The fermented residue which has been left from the fermentation process still can be utilized for bioethanol production (Zhao et al., 2010). Thus, this study evaluated the energy and mass balance of bamboo as a feedstock for bioethanol

Please cite this article as: Ko C. H., Wang Y. N., Chang F. C., Lee C. Y., Chen W. H., Hwang W. S., 2013, Energy analysis of bioethanols produced from dendrocalamus latiflorus, Chemical Engineering Transactions, 34, 109-114 DOI:10.3303/CET1334019

production. Several processes included acidic steam explosion, alkaline steam explosion, bleached, unbleached kraft pulps, enzyme hydrolysis, and simultaneous saccharification and fermentation (SSF) for fuel ethanol production from bamboo were studied through energy consumption and energy production. Additionally, the energy use of the compacting fermented residue was also analyzed.

2. Methodology

2.1 Materials

The Ma Bamboo (*Dendrocalamus latiflorus* Munro) sample, approx. 4-year-old Ma Bamboo culms, was collected from the Experimental Forest of National Taiwan University. The stem was chopped into 6 × 3 cm (length × width), then air dried for a month.

2.2 Methods

Air-dried bamboo sample was soaked into 1.5 % H_2SO_4 solution or 1.5 % NaOH & Na_2SO_3 solution for a week. Steam explosion conditions were: solid/liquid ratio=1:7; temperature and pressure of alkali-treated samples were held at 190 °C for 5 min. Acid-treated sampled were held at 190 °C for 10 min. Bamboo air-dried kraft pulp was cooked by M/K digester with wood to liquid ratio (w/v) of 0.25, 25 % sulfidity, and 17 % active alkali. H-factor is about 650, with temperature raised at 1.5 °C/min to 160 °C in 90 min, then kept at 160 °C for another 90 min. Bleached pulps were prepared from the kraft pulps by a commercial DEDD (D: chlorine dioxide; E: alkali extraction) bleaching sequence (Ko et al., 2010). Acid and alkali steam-exploded bamboo pulps were hydrolyzed with a combination of Novozymes® 50010 and 50013 cellulose complexes. Hydrolysis was conducted in a total volume of 200 mL liquid with 0.05 M citrate buffer (pH 5) and 2.5 % (w/v) samples in a 250 mL conical flask. One hundred mL of reaction solution, with 5 % (w/v) steam-exploded bamboo, 1 % (w/v) yeast extract, and 2 % (w/v) peptone, was subject to 38 °C and pH 5 in a 250 mL conical flask.

Oven-dried bamboo chips and steam exploded samples were hand-kneaded before the compositional analyses for acid-insoluble lignin, holocellulose, and α-cellulose. Enzymatic hydrolysate and SSF samples were analyzed by high performance liquid chromatography (HPLC) using an IC Sep ION-300 column and an RI detector for identifying alcohols and mono sugars at 70 °C, with sulphuric acid (0.0085 N) as the mobile phase eluted at flow rate of 0.4 mL/min.

2.3 Energy analysis

The relevant processes in the biomass production and the conversion to bioethanol are considered within the system boundaries of the bioethanol life cycle. Energy consumption analyses for production of bioethanol from lignocellulosic biomass steam explosion processing were followed by the process of Chen et al. (2011). One L of bioethanol that was produced from feedstock would need 5 kg of rice hull (conversion ratio: 0.2 L/kg). Kraft pulping and bleaching energy consumption estimation was calculated according to the Chung-Hwa Pulp Corporation factory (Electricity consumption: 334 kWh/t-pulp and fuel oil 159.5 L/ton-pulp). The energy consumption of kraft pulping and bleaching pulp is about 5,885 MJ/ton pulp and 7,345 MJ/t pulp, respectively. Kraft pulp ethanol energy consumption: 5885 (MJ/ton-pulp) / 30 % (from pulp to ethanol) = 19.62 MJ/kg-ETOH. Bleached pulp ethanol energy consumption: 7345 (MJ/ ton-pulp) / 38 % (from pulp to ethanol) = 19.33 MJ/kg-ETOH. When the SSF conversion was considered, the energy pulping energy consumption from pulp to bioethanol is 15.48 MJ/L EtOH and 15.25 MJ/L EtOH. The fermented solid residue after simultaneous saccharification and fermentation could still be used as solid-compacting fuel after compacting. The ultimate analysis and high heating value (HHV) of the fermented solid residue also were calculated according to the procedure by Demirbas (1997) and the more recent one by Sheng and Azevedo (2005).

3. Results and discussion

3.1 Ethanol production of bamboo

The bamboo covers 152,300 ha, with overall volume of 535,000 m^3 in Taiwan. Its mass growth was estimated at 10-25 %. Assuming 160,000 m^3 (80,000 t) of bamboo were harvested annually, Table 1 lists annual ethanol production from bamboo estimated by SSF following different pretreatments. Annual ethanol production of bamboo by acid steam explosion and bleached pulp pretreatment is greater than 10,000 t. Ethanol production of bamboo by alkali steam explosion is relatively lower. This is because that the ethanols yield of bamboo by alkali steam explosion is only 0.3-0.5 times than that by acid steam explosion, kraft pulp, and bleached pulp pretreatment.

Table 1: Annual ethanol production from bamboo estimated by SSF following different pretreatments

	Pretreatment yield (%)	Ethanol yield (g EtOH / g pulp)	Raw material to ethanol (%)	Estimate yield (10^4 t/y)
Acid steam explosion	57	0.23	13.40	1.07
Alkali steam explosion	80	0.11	8.96	0.72
Kraft pulp	40	0.30	12.16	0.97
Bleached pulp	39.8	0.38	15.25	1.22

3.2 Ethanol energy consumption

In this study, when producing 1 kg ethanol from acidic and alkali (190 ^{o}C and 5 min) steam explosion pretreatment, 6.25 and 9.09 kg of Ma bamboo chip are provided (conversion ratio: 0.20 and 0.11 L/kg), respectively. Energy consumption of produced ethanol by steam explosion and SSF is shown in Table 2 (Ethanol density: 0.79 g/cm^3). When producing 1 L of ethanol by kraft pulp and bleached pulp pretreatment, 5.85 and 5.0 kg of Ma bamboo chip are provided (conversion ratio: 0.17 and 0.20 L/kg), respectively. Energy consumption of produced ethanol by kraft pulp or bleached pulp through SSF is shown in Table 2.

Table 2: Energy consumption for ethanol by steam explosion, SSF, kraft pulp and bleached pulp

Energy Use (MJ/L ethanol)	Acid	Alkali	Kraft pulp	Bleached pulp
Pretreatment or Pulping	23.69	34.45	15.48	15.25
Electricity/Steam	3.20/20.00	4.65/29.09	-	-
Acid/Alkali Production	0.15/0.34	0.22/0.49	-	-
SSF	8.93	13.00	8.40	7.14
Electricity /Enzyme/Yeast	7.01/1.84/0.08	10.20/2.68/0.12	6.60/1.73/0.07	5.61/1.47/0.06
Product Recovery	10.84	15.77	10.21	8.67
Steam/Cooling Water	10.25/0.33	14.91/0.48	9.65/0.31	8.20/0.26
Wastewater Treatment/Dehydrate	0.21/0.05	0.31/0.07	0.20/0.05	0.17/0.04
Total Energy Use	44.35	64.51	34.08	31.06

3.3 Energy use of compacting the fermented residue

The ultimate analysis and high heating value (HHV) of the fermented solid residue are shown in Table 3. The carbon content was the decisive factor of HHV, after SSF the carbon content of residues increased and HHV increased except the pulp 200 ^{o}C and 10 min was decreased.

Table 4 shows the energy consumption of the SSF residue from 1 kg Ma bamboo material in the compacting process. The moisture content of SSF residue is about 33 % after squeezing, and then dehydrated to 15 % before compacting. The dehydrated energy consumption that was calculated as vaporization heat of water was about 2.26 MJ/kg. Energy consumption of compacted process was 0.0235 (MJ/kg) following Mani et al. (2006).

3.4 Energy and mass balance

Ma bamboo chip was pretreated to pulps through ethanol-production process and residue compacted, then ethanol and compacting fuel produced. The energy content (HHV) and mass difference from ethanol production process were listed in Table 5. Ma bamboo chip HHV (18.06 MJ/kg), then steam explosion, kraft and bleached pulps were about 6.59-14.46 MJ left. Acidic steam explosion pulp (21.71 MJ/kg) for example, 0.57 kg pulp from per kg Ma bamboo chip, produced ethanol 0.131 kg (HHV: 26.8 MJ/kg) and 0.15 kg compacting fuel (24.4 MJ/kg), 7.17 MJ energy in total.

Table 3: Ultimate analysis of bamboo and its HHV

Samples	C (%)	H (%)	N (%)	O* (%)	Ash (%)	HHV (MJ/kg)	HHV_{ult} (MJ/kg)	HHV_{prox} (MJ/kg)
Bamboo	46.91	6.46	0.39	44.54	1.70	18.06	18.75	19.52
Acid steam explosion	54.56	5.83	0.44	31.57	7.6	21.71	21.24	18.15
Alkali steam explosion	43.64	6.14	0.27	44.55	5.40	16.53	17.68	18.66
Kraft pulp	42.46	6.49	0.10	50.31	0.64	15.77	17.30	19.77
Bleached pulp	42.18	6.51	0.10	50.31	0.90	15.70	17.21	19.70

*O (%) = 100-C-H-N-Ash; HHV (High heating value)=[33.5(C)+142.3(H)-15.4(O)-14.5(N)]×10-2; HHVult (Ultimate analysis formula)= 0.3259(C)+3.4597; HHVprox (Proximate analysis formula)= 19.914-0.2324 (Ash).

Table 4: Energy consumption of the compacting process from 1 kg material

Pulps	Dehydrate (kg)	Consumption energy (MJ)	Compacted residue (kg)	Consumption energy (MJ/kg)
Acid steam explosion	0.05	0.11	0.15	0.004
Alkali steam explosion	0.21	0.47	0.68	0.016
Kraft pulp	0.05	0.11	0.15	0.004
Bleached pulp	0.02	0.05	0.05	0.001

Table 5: The HHV and mass layout from ethanol production process

Ma bamboo (1 kg)	Pretreated yield (kg)	HHV_{pulp} (MJ/kg)	Energy (MJ)	Compacted after SSF(kg)	$HHV_{residue}$ (MJ/kg)	Energy (MJ)	EtOH Yield (kg)	Energy (MJ)
Acid steam explosion	0.57	21.71	12.37	0.15	24.40	3.66	0.131	3.51
Alkali steam explosion	0.80	18.08	14.46	0.68	16.71	11.36	0.088	2.36
Kraft pulp	0.45	15.77	7.10	0.15	15.77	2.37	0.135	3.62
Bleached pulp	0.42	15.70	6.59	0.05	15.70	0.79	0.160	4.29

* HHVethanol = 26.8 MJ / kg (according to Thomas (2000))

If 1 kg of ethanol was produced as energy output 26.8 MJ without fermented residue utilization, the steam explosion pulps and kraft pulps was all net energy negative. As shown in Table 6, the 4 kinds of pulp had different energy consumption per kg ethanol. Estimated ethanol production and compacted energy use (MJ/kg chip) from Ma bamboo chip is shown in Table 7. The net energy value of acidic steam explosion pulp, alkali steam explosion, kraft pulp, and bleached pulp is -1.75, 4.42, -2.71, and 2.90 MJ/kg chip. The alkali steam explosion has highest net energy value and is equivalent to 50.22 MJ/kg ethanol. The flowchart of the energy balance for alkali steam explosion is shown in Figure 1.

To compare our results with those of other authors, we compiled data obtained from several studies that evaluated the energy analysis of bioethanol from cellulosic feedstock. The net energy values of biomass conversion to ethanol are lower than Luo et al. (2009) (114.43 MJ/kg) and higher than Goh and Lee (2010) (31.56 MJ/kg), Papong and Malakul (2010) (-4.71 MJ/kg), and Cardona Alzate and Sanchez Toro (2006) (22.37-23.99 MJ/kg). In the present study, field data obtained from a production-scale commercial kraft pulp mill and a ton per day pilot bioethanol plant were used. Due to differential industrial layout and prectice, the energy values in the present are reasonably different from other reported values. Major energy consumption comes from the ethanol conversion stage which accounts for 76.34 % of the total energy usage. This ethanol production/conversion stage has shown to contribute most to the environmental impact when compared with other stages (Papong and Malakul, 2010). The result is similar with Papong and Malakul (2010) (78 % of the total energy usage). From the result of energy balance, the bioethanol produced from bamboo seems to be an important and indispensable bioenergy.

Table 6: Estimated ethanol production energy from chip to ethanol

Energy Use (MJ/kg ethanol)	Acid	Alkali	Kraft	Bleached
Pretreatment or Pulping	30.01	43.65	19.62	19.33
Electricity/ Steam	4.06/25.35	5.89/36.87	-	-
Acid/ Alkali Production	0.19/0.43	0.28/0.62	-	-
SSF	11.32	16.46	10.65	9.05
Electricity/ Enzyme/Yeast	8.88/2.33/0.10	12.93/3.40/0.15	8.37/2.19/0.09	7.11/1.86/0.08
Product Recovery	13.74	19.99	12.93	10.99
Steam/ Cooling Water	12.99/0.42	18.90/0.61	12.23/0.39	10.39/0.33
Wastewater Treatment/Dehydrate	0.27/0.06	0.39/0.09	0.25/0.06	0.22/0.05
Total energy use	55.07	80.10	43.2	39.37

According to the energy statistical annual report (Bureau of Energy, 2010), the consumption of petroleum in Taiwan is about 49,498,800 MLOE annually, transportation part 29.5 % (14,599,000 MLOE; approximately 10,949,250 ton). In this study, the bamboo optimistic annually growth was 1,328,000 available as feedstock. As much as 174,100 tons of bioethanols could be produced annually by acidic steam explosion (74 % of energy demand as E3 additive policy), 116,900 tons of that by alkali steam explosion (190 ^{o}C and 5 min) (50 % of energy demand as E3 additive policy), and 211,900 tons of that by bleached pulp (90 % of energy demand as E3 additive policy).

Table 7: Estimated ethanol production and compacted energy use from Ma bamboo chip

Energy Use (MJ/kg chip)	Acidic	Alkali	Kraft Pulp	Bleached Pulp
Ethanol conversion (L/kg)	0.16	0.11	0.17	0.20
Pretreatment or Pulping	4.80	4.80	3.87	3.92
Electricity/ Steam	0.65/4.06	0.65/4.06	-	-
Acid/Alkali Production	0.03/0.07	0.03/0.07	-	-
SSF	1.81	1.81	2.13	1.81
Electricity/ Enzyme/Yeast	1.42/0.37/0.02	1.42/0.37/0.02	1.67/0.44/0.02	1.42/0.37/0.02
Product Recovery	2.20	2.20	2.59	2.20
Steam/ Cooling Water	2.08/0.07	2.08/0.07	2.45/0.08	2.08/0.07
Wastewater Treatment/ Dehydrate	0.04/0.01	0.04/0.01	0.05/0.01	0.04/0.01
Residue dehydrated/ Compacted	0.11/0.004	0.47/0.016	0.11/0.004	0.05/0.001
Total energy use	8.92	9.30	8.70	7.98

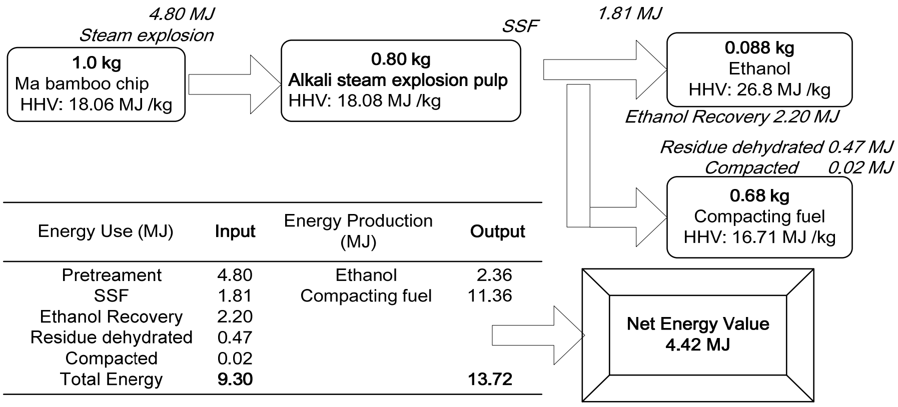

Figure 1: Energy value of bamboo by alkali steam explosion pulp

4. Conclusion

Biomass derived by photosynthesis has strong potentials from bioethanol production. Results show that the post-fermentation residues possessed high heating values. The net energy value of bamboo by alkali steam explosion is about 39.67 MJ/L ethanol. The net energy gains could be achieved for the processes with greater ethanol yields: acid steam explosion and fully bleached pulps. SSF could produce 220 ML of bioethanols from by acidic steam explosion pulps and 148 ML of bioethanols by alkaline steam explosion pretreatment pulps annually. This study demonstrated potentials of the indigenous bamboo storage as a source for bioethanol production. Additionally, planned harvesting of bamboos will maximize its carbon sequestration potential without ecological damage. Afforestation to provide biomass could also provide additional habitats and slope stabilization for mountain regions.

References

Bureau of Energy, 2010, Energy statistical annual report, Bureau of Energy, Ministry of Economic Affairs, Taiwan, R.O.C.

Cardona Alzate C.A., Sanchez Toro O.J., 2006, Energy consumption analysis of integrated flowsheets for production of fuel ethanol from lignocellulosic biomass, Energy, 31, 2447-2459.

Ceclan R.E., Pop A., Ceclan M., 2012, Studies concerning the integrated use of sweet sorghum for bioethanol production in Romania, Chemical Engineering Transactions, 29, 877-882.

Chen W.H., Pen B.L., Yu C.T., Hwang W.S., 2011, Pretreatment efficiency and structural characterization of rice straw by an integrated process of dilute-acid and steam explosion for bioethanol production, Bioresource Technology, 102, 2916-2924.

Demirbas A., 1997, Calculation of higher heating values of biomass fuels, Fuel, 76, 431-434.

Goh C.S., Lee K.T., 2010, Palm-based biofuel refinery (PBR) to substitute petroleum refinery: An energy and emergy assessment, Renew. Sust. Energ. Rev., 14, 2986-2995.

Ko C.H., Lin Z.P., Tu J., Tsai C.H., Liu C.C., Chen H.T., Wang T.P., 2010, Xylanase production by Paenibacillus campinasensis BL11 and its pretreatment of hardwood kraft pulp bleaching. Int. Biodeterior. Biodegrad., 64, 13-19.
Li M.F., Fan Y.M., Xu F., Sun R.C., Zhang X.L., 2010, Cold sodium hydroxide/urea based pretreatment of bamboo for bioethanol production: Characterization of the cellulose rich fraction, Ind. Crop. Prod., 32, 551-559.
Luo L., van der Voet E., Huppes G., 2009, An energy analysis of ethanol from cellulosic feedstock–Corn stover, Renew. Sust. Energ. Rev., 13, 2003-2011.
Mani S., Tabil L.G., Sokhansanj S., 2006, Specific energy requirement for compacting corn stover, Bioresource Technology, 97, 1420-1426.
Papong S., Malakul P., 2010, Life-cycle energy and environmental analysis of bioethanol production from cassava in Thailand, Bioresource Technology, 101, 112-118.
Sheng C., Azevedo J., 2005, Estimating the higher heating value of biomass fuels from basic analysis data, Biomass Bioenergy, 28, 499-507.
Shimokawa T., Ishida M., Yoshida S., Nojiri M., 2009, Effects of growth stage on enzymatic saccharification and simultaneous saccharification and fermentation of bamboo shoots for bioethanol production, Bioresource Technology, 100, 6651-6654.
Theuretzbacher F., Kravanja P., Becker M., Bauer A., Amon B., Friedl A., Potthast A., Amon T., 2012, Utilization of sweet sorghum as a catch crop for providing raw materials for the production of bioethanol and biogas, Chemical Engineering Transactions, 29, 1135-1140.
Thomas G., 2000, Overview of storage development DOE hydrogen program, US DOE Hydrogen Program 2000 Annual Review, 9-11.
Yamashita Y., Shono M., Sasaki C., Nakamura Y., 2010, Alkaline peroxide pretreatment for efficient enzymatic saccharification of bamboo, Carbohydr. Polym., 79, 914-920.
Zhao X., Zhou Y., Zheng G., Liu D., 2010, Microwave pretreatment of substrates for cellulase production by solid-state fermentation, Appl. Biochem. Biotechnol., 160, 1557-1571.