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Global potential bioethanol production from wasted crops and crop residues

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Abstract

The global annual potential bioethanol production from the major crops, corn, barley, oat, rice, wheat, sorghum, and sugar cane, is estimated. To avoid conflicts between human food use and industrial use of crops, only the wasted crop, which is defined as crop lost in distribution, is considered as feedstock. Lignocellulosic biomass such as crop residues and sugar cane bagasse are included in feedstock for producing bioethanol as well. There are about 73.9 Tg of dry wasted crops in the world that could potentially produce 49.1 GL year^{-1} of bioethanol. About 1.5 Pg year^{-1} of dry lignocellulosic biomass from these seven crops is also available for conversion to bioethanol. Lignocellulosic biomass could produce up to 442 GL year^{-1} of bioethanol. Thus, the total potential bioethanol production from crop residues and wasted crops is 491 GL year^{-1}, about 16 times higher than the current world ethanol production. The potential bioethanol production could replace 353 GL of gasoline (32% of the global gasoline consumption) when bioethanol is used in E85 fuel for a midsize passenger vehicle. Furthermore, lignin-rich fermentation residue, which is the coproduct of bioethanol made from crop residues and sugar cane bagasse, can potentially generate both 458 TWh of electricity (about 3.6% of world electricity production) and 2.6 EJ of steam. Asia is the largest potential producer of bioethanol from crop residues and wasted crops, and could produce up to 291 GL year^{-1} of bioethanol. Rice straw, wheat straw, and corn stover are the most favorable bioethanol feedstocks in Asia. The next highest potential region is Europe (69.2 GL of bioethanol), in which most bioethanol comes from wheat straw. Corn stover is the main feedstock in North America, from which about 38.4 GL year^{-1} of bioethanol can potentially be produced. Globally rice straw can produce 205 GL of bioethanol, which is the largest amount from single biomass feedstock. The next highest potential feedstock is wheat straw, which can produce 104 GL of bioethanol. This paper is intended to give some perspective on the size of the bioethanol feedstock resource, globally and by region, and to summarize relevant data that we believe others will find useful, for example, those who are interested in producing biobased products such as lactic acid, rather than ethanol, from crops and wastes. The paper does not attempt to indicate how much, if any, of this waste material could actually be converted to bioethanol.

Keywords: Biomass energy; Bioethanol production; E85 fuel; Lignocellulosic biomass; Starch crop

1. Introduction

Biomass energy currently contributes 9–13% of the global energy supply—accounting for 45 ± 10 EJ per year [1]. Biomass energy includes both traditional uses

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(e.g., firing for cooking and heating) and modern uses (e.g., producing electricity and steam, and liquid biofuels). Use of biomass energy in modern ways is estimated at 7 EJ a year, while the remainder is in traditional uses. Biomass energy is derived from renewable resources. With proper management and technologies, biomass feedstocks can be produced sustainably.

Ethanol derived from biomass, one of the modern forms of biomass energy, has the potential to be a sustainable transportation fuel, as well as a fuel oxygenate that can replace gasoline [2]. Shapouri et al. [3,4] concluded that the energy content of ethanol was higher than the energy required to produce ethanol. Kim and Dale [5] also estimated the total energy requirement for producing ethanol from corn grain at 560 kJ MJ^{-1} of ethanol, indicating that ethanol used as a liquid transportation fuel could reduce domestic consumption of fossil fuels, particularly petroleum.

The world ethanol production in 2001 was 31 GL [6]. The major producers of ethanol are Brazil and the US, which account for about 62% of world production. The major feedstock for ethanol in Brazil is sugar cane, while corn grain is the main feedstock for ethanol in the US. Ethanol can be produced from any sugar or starch crop. Another potential resource for ethanol is lignocellulosic biomass, which includes materials such as agricultural residues (e.g., corn stover, crop straw, sugar cane bagasse), herbaceous crops (e.g., alfalfa, switchgrass), forestry wastes, wastepaper, and other wastes [7]. The utilization of lignocellulosic biomass for fuel ethanol is still under development.

This study estimated how much bioethanol can potentially be produced from starch, sugar crops, and agricultural residues. These crops include corn, barley, oat, rice, wheat, sorghum, and sugar cane. To avoid conflicts between food use and industrial uses of crops, only wasted crops are assumed to be available for producing ethanol. Wasted crops are defined as crops lost during the year at all stages between the farm and the household level during handling, storage, and transport. Waste of the edible and inedible parts of the commodity that occurs after the commodity has entered the household and the quantities lost during processing are not considered here. The agricultural residues include corn stover, crop straws, and sugar cane bagasse, generated during sugar cane processing.

2. Data source and data quality

The data for biomass (e.g., crop production, yield, harvested area, etc.) are obtained from FAO statistics (FAOSTAT) [8]. Average values from 1997 to 2001 are used in this study. Some nations are selected to compare their national data for crop production, available in their government websites, with the data presented in FAOSTAT for those some countries. The analysis points out that there are some disparities between the two datasets in some nations, as presented in Table 1. Although large uncertainties in some nations would be expected, the values provided by FAOSTAT are used in this study without any modification due to the following reasons: (1) there are currently no official data available but FAOSTAT, (2) it would be very difficult to collect the data from every country. Except for the country of Mexico and except for rice as a crop, the national data and the FAOSTAT data are actually quite consistent, when national data are available.

3. Composition of crops and ethanol yield

Table 2 shows the composition of biomass (carbohydrates and lignin) and the fraction of crop residues produced. It also presents the potential ethanol yield. Carbohydrates, which include starch, sugar, cellulose, and hemicelluloses, are the main potential feedstocks for producing bioethanol. Lignin can be used to generate electricity and/or steam. Crop residues are a major potential feedstock for bioethanol. For example, corn stover plays an important projected role in lignocellulose-based bioethanol production [9].

Ethanol from grains is assumed to be produced by the dry milling process, in which starch in grain is converted into dextrose, and then ethanol is produced in fermentation and separated in distillation. Ethanol yield from grain is estimated based on its starch content [9].

A report published by the US National Renewable Energy Laboratory (NREL) [9] showed that 288–447 l of ethanol per one dry ton of corn stover could be produced. Ethanol yield in lignocellulosic feedstocks is estimated from the US Department of Energy website, which provides "Theoretical Ethanol Yield Calculator" [10], assuming that ethanol

Table 1
Differences between FAO data and national data

	Differences between data in FAOSTAT and national data[a] (%)						
	Corn	Barley	Oat	Rice	Wheat	Sorghum	Sugar cane
Brazil	n.a.[b]	n.a.	n.a.	0.1	8.7	n.a.	0.9
Canada	0.5	0.1	0.1	n.a.	0.0	n.a.	n.a.
India	0.6	n.a.	n.a.	n.a.	n.a.	n.a.	0.8
Indonesia	2.7	n.a.	n.a.	0.2	n.a.	n.a.	n.a.
Japan	n.a.	0.0	n.a.	24.9	0.0	n.a.	n.a.
Korea	0.1	n.a.	n.a.	34.1	n.a.	n.a.	n.a.
Mexico	1.6	24.7	33.5	26.6	0.7	5.5	n.a.
Philippines	0.0	n.a.	n.a.	n.a.	n.a.	n.a.	12.9
UK	n.a.	0.1	0.1	n.a.	0.1	n.a.	n.a.
US	0.1	0.1	0.1	0.4	0.1	0.1	0.0

[a]Data in FAOSTAT—data in national database |/ data in national database.
[b]Not available.

Table 2
Composition of crops (based on dry mass) [10–14]

	Residue/crop ratio	Dry matter (%)	Lignin (%)	Carbohydrates (%)	Ethanol yield (L kg^{-1} of dry biomass)
Barley	1.2	88.7	2.90	67.10	0.41
Barley straw		81.0	9.00	70.00	0.31
Corn		86.2	0.60	73.70	0.46
Corn stover		78.5	18.69	58.29	0.29
Oat	1.3	89.1	4.00	65.60	0.41
Oat straw		90.1	13.75	59.10	0.26
Rice	1.4	88.6		87.50	0.48
Rice straw		88.0	7.13	49.33	0.28
Sorghum	1.3	89.0	1.40	71.60	0.44
Sorghum straw		88.0	15.00	61.00	0.27
Wheat	1.3	89.1		35.85	0.40
Wheat straw		90.1	16.00	54.00	0.29
Sugarcane		26.0		67.00	0.50
Bagasse	0.6[a]	71.0	14.50	67.15	0.28

[a]kg of bagasse per kg of dry sugar cane.

production efficiency from other crop residues is equal to that of ethanol production from corn stover.

4. Removal of crop residues

The full utilization of some crop residues may give rise to soil erosion and decrease soil organic matter [15]. The fraction of crop residues collectable for biofuel is not easily quantified because it depends on the weather, crop rotation, existing soil fertility, slope of the land, and tillage practices. According to the US Department of Agriculture [16], conservation tillage practices for crop residue removal require that 30% or more of the soil surface be covered with crop residues after planting to reduce soil erosion by water (or 1.1 Mg per hectare of small grain residues to reduce soil erosion by wind). In this study, a 60% ground cover, instead of a 30%, is applied due to the uncertainties of local situations.

More than 90% of corn stover in the United States is left in the fields. Less than 1% of corn stover is collected for industrial processing, and about 5% is baled for animal feed and bedding [17]. Utilization of crop residues for animal feed and bedding is not taken into account in this study because it is too low, although the utilization fraction may vary with the geographic region.

5. Fuel economy

Ethanol is used as an alternative vehicle fuel, for example, as E85—a mixture of 85% ethanol and 15% of gasoline by volume. The fuel economy in a midsize passenger vehicle is 11 l 100 km^{-1} in conventional fuel and 10.3 gasoline-equivalent liter 100 km^{-1} in E85 fuel [18]. One hundred-km driven by a conventional gasoline-fueled midsize passenger car requires 11 l of gasoline. For E85 fuel, 100-km driven consumes 2.2 l of gasoline and 12 l of bioethanol. Therefore, 1 l of bioethanol could replace 0.72 liters of gasoline.

6. Results

6.1. Corn

6.1.1. Global situation

About 520 Tg of dry corn is produced annually in the world. The major production regions are North America (42%), Asia (26%), Europe (12%) and South America (9%). Regarding corn yield, the highest yield occurs in North America, in which 7.2 Mg of dry corn per hectare is produced. The next highest yield occurs in Oceania (5.2 dry Mg ha^{-1}). Africa has the lowest yield, 1.4 dry Mg ha^{-1}. The global average yield is 3.7 dry Mg ha^{-1}. The US is the largest producer of corn, about 40% of global production. The second largest producer is China with 20% of global production. The highest yield occurs in Kuwait, 16.5 dry Mg ha^{-1}.

Most corn (about 64% of global production) is used for animal feed. Food use for humans is the second largest application, about 19% of global production. In Africa and Central America, most corn is used for human food, while animal feed is the major use of corn in the other regions (see Table 3). About 5% of global production is lost as waste. According to FAOSTAT, waste is defined as crop lost in the year at all stages between the farm and the household level during handling, storage, and transport. Waste of the edible and inedible parts of the commodity that occurs after the commodity has entered the household and the quantities lost during processing are not considered. Thus, the wasted crop is a logistic waste. The highest loss rate occurs in Central America, averaging over 9% of its corn production.

6.1.2. Potential bioethanol production from corn

About 5% of corn in the world is wasted. If wasted corn could be fully utilized as feedstock for producing bioethanol, then 9.3 GL of bioethanol could be produced, thereby replacing 6.7 GL of gasoline if bioethanol is used as an alternative vehicle fuel, E85.

Furthermore, if bioethanol is produced using the corn dry milling process, in which 922 g of dry distillers' dried grains and solubles (DDGS) per kg of ethanol is produced as a coproduct, about 11 Tg of DDGS are available for animal feed and replace 13 Tg of corn used as animal feed [2]. If we suppose that the replaced corn due to DDGS is utilized in producing bioethanol, then another 5.1 GL of bioethanol (equivalent to 3.7 GL of gasoline used in a midsize passenger car fueled by E85) could be produced. The wasted corn could reduce around 0.93% of global gasoline consumption annually (10.3 GL of gasoline).

Corn stover, the crop residue in the cornfield, is produced at a rate of 1 dry kg per dry kg of corn grain. A 60% ground cover requires 2.7 Mg of corn stover per hectare [19]. Under this practice, about 203.6 Tg of dry corn stover are globally available, potentially resulting in about 58.6 GL of bioethanol. The potential amount of bioethanol derived from corn stover could replace 42.1 GL of gasoline used in a midsize passenger vehicle fueled by E85, or about 3.8% of world annual gasoline consumption.

Lignin-rich fermentation residues are generated during corn stover-based processing to bioethanol [9]. These residues can be used as feedstock for generating electricity and steam. The efficiency of generating electricity from biomass in an integrated gasification combined cycles power plant is about 32%, and the efficiency of generating steam is 51% [20]. If all the

Table 3
Uses of corn grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	24.27	1.40	8.61	1.38	63.43	0.92
Asia	60.50	1.47	7.14	3.41	24.33	3.16
Europe	79.21	0.85	2.51	7.23	6.68	3.51
North America	75.38	0.27	0.14	18.55	1.99	3.67
Central America	29.56	1.77	9.49	4.18	54.71	0.29
Oceania	72.96	0.28	3.16	0.52	18.04	5.04
South America	71.99	0.94	8.55	1.23	15.10	2.19
World	64.20	0.96	4.60	8.60	18.67	2.97

Table 4
Regional electricity and steam produced from utilization of corn stover

	Electricity (TWh)	Steam (PJ)
Africa	—	—
Asia	15.0	86.1
Europe	12.7	72.7
North America	59.2	339.6
Central America	—	—
Oceania	0.1	0.6
South America	3.2	18.3
World	90.2	517.3

lignin remains in the bioethanol residue, corn stover utilization could generate both 90.2 TWh of electricity and 517 PJ of steam. The electricity that could be produced from lignin-rich fermentation residues from corn stover ethanol plant is equivalent to 0.7% of total global electricity generation. Table 4 illustrates electricity and steam generated from lignin-rich corn stover fermentation residues. Africa and Central America do not have corn stover available for conversion to bioethanol due to low corn yield and the overriding need to prevent erosion.

Table 5 shows the regional potential bioethanol production from wasted corn grain and corn stover. Annually, 73 GL of bioethanol are available from wasted corn and corn stover, replacing 52.4 GL of gasoline per year, which is equivalent to about 4.7% of the world annual gasoline consumption. North America can produce over 35 GL of bioethanol if wasted corn grain and corn stover are fully utilized as feedstocks for bioethanol.

6.2. Barley

6.2.1. Global situation

The annual production of dry barley in the world averages about 124 Tg. Europe (62%), Asia (15%), and North America (14%) are the major production regions. The fraction of barley production in the other regions is less than 5%. The barley yield ranges from 0.74 to 2.8 dry Mg ha^{-1} with the global average 2.3 dry Mg ha^{-1}. The highest yield occurs in Europe with 2.8 Mg of dry barley per hectare.

Germany is the largest producer of barley with a yield of 5.3 dry Mg ha^{-1}, and contributes to 9.3% of global production. The second largest producer is Canada with 9.1% of global production. The yield of barley in Canada is 2.6 dry Mg ha^{-1}, and Canada has the largest harvested area for barley (7.6% of global harvested area for barley). The highest yield occurs in Ireland, 5.7 dry Mg ha^{-1}.

Like corn, most barley grain (about 67% of production) is used for animal feed. Barley use for food manufacture is the second largest application. About 4% of global barley production is lost during the logistics, as shown in Table 6.

6.2.2. Potential bioethanol production from barley

About 3.4% of barley in the world, 3.7 Tg, is lost as waste. If wasted barley could be fully utilized to produce bioethanol, then 1.5 GL of bioethanol could be produced globally, replacing 1.1 GL of gasoline if ethanol is used as E85 fuel for a midsize passenger vehicle.

Furthermore, DDGS, a coproduct in barley dry milling to ethanol, could replace barley grain that is

Table 5
Regional potential bioethanol production from wasted corn grain and corn stover

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From corn stover	Total bioethanol (GL)	Gasoline equivalent[a] (GL)
Africa	1.40	0.77	—	2.17	1.56
Asia	4.41	2.41	9.75	16.6	11.9
Europe	0.71	0.39	8.23	9.32	6.7
North America	0.14	0.08	38.4	38.7	27.8
Central America	0.78	0.428	—	1.21	0.87
Oceania	0.01	0.004	0.07	0.08	0.06
South America	1.86	1.01	2.07	4.94	3.55
World	9.3	5.08	58.6	73.0	52.4

[a]Ethanol is used as fuel in E85 for a midsize passenger car.

Table 6
Uses of barley grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	30.20	6.98	5.77	12.14	44.57	0.34
Asia	54.18	5.93	6.73	19.91	9.70	3.55
Europe	75.19	9.52	2.59	11.05	1.38	0.27
North America	74.99	3.48	0.04	20.49	0.93	0.07
Central America	29.07	1.38	2.22	65.11	1.90	0.33
Oceania	78.47	5.50	3.08	12.77	0.15	0.03
South America	11.03	2.78	3.35	73.69	7.29	1.85
World	66.74	7.54	3.39	15.99	5.32	1.03

used for animal feed. Since the information on DDGS from barley dry milling is currently unavailable, corn dry milling data are used instead, and 1 dry kg of DDGS from barley dry milling is assumed to replace 1 kg of dry barley grain in the market. This assumption is applied to all the crops in this study. The total amount of DDGS from barley dry milling is 2.4 dry Tg if wasted barley grain is utilized by dry milling. About 2.4 Tg of dry barley grain are saved due to DDGS and could produce 0.96 GL of bioethanol. Hence, the wasted barley grain can produce globally about 1.8 GL of bioethanol.

The 60% ground cover with crop residue is assumed to require 1.7 Mg per hectare of barley residues, which is an equivalent quantity in wheat and oats [19]. After providing the 60% ground cover, about 18 GL of bioethanol could be available from barley straw (see Table 2). All the lignin in barley straw is assumed to remain in the fermentation residues, and could generate both 12.5 TWh of electricity and 71.5 PJ of steam.

Overall barley could produce 20.6 GL of bioethanol per a year if wasted grain and barley straw are utilized. The bioethanol from barley potentially replaces 1.3% of global gasoline consumption without taking barley from other applications. Europe itself could produce 15.1 GL of bioethanol from wasted barley and barley straw. Very little wasted barley grain is available for bioethanol in North America. However, there is a good opportunity to utilize barley straw as feedstock for producing bioethanol in North America. The regional potential bioethanol production from barley is shown in Table 7.

Table 7
Regional potential bioethanol production from wasted barley grain and barley straw

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From barley straw	Total bioethanol (GL)	Gasoline equivalent (GL)
Africa	0.07	0.05	—	0.12	0.08
Asia	0.50	0.32	0.61	1.44	1.03
Europe	0.82	0.53	13.7	15.1	10.8
North America	0.003	0.002	3.06	3.06	2.20
Central America	0.005	0.003	0.05	0.06	0.04
Oceania	0.08	0.05	0.60	0.73	0.52
South America	0.02	0.01	0.09	0.12	0.09
World	1.50	0.96	18.1	20.6	14.8

Table 8
Uses of oat grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	39.84	8.07	2.78	0.02	49.29	0.00
Asia	66.90	7.85	5.69	0.00	19.52	0.03
Europe	72.95	17.61	2.75	0.00	6.56	0.13
North America	75.90	5.47	0.21	0.00	18.42	0.00
Central America	72.41	1.14	0.73	0.00	25.71	0.00
Oceania	91.01	5.71	0.11	0.00	3.11	0.06
South America	44.58	16.75	4.69	0.00	33.98	0.00
World	72.77	13.58	2.27	0.00	11.29	0.09

6.3. *Oats*

6.3.1. *Global situation*

The annual production of dry oats in the world is 24.2 Tg. The major production regions are Europe (64%), North America (21%), and Oceania (5%). The yield in most regions ranges from 1.4 to 2.1 dry Mg ha^{-1}, and the global average yield is 1.8 dry Mg ha^{-1}. Russia is the largest producer of oats in the world with 24% of global production (6.4 dry Tg). The highest yield occurs in Ireland, 6.0 dry Mg ha^{-1}, over three times higher than the global average yield.

Table 8 shows the use fraction of oat grain. About 73% of global oat production is consumed as animal feed. The fraction of oats used for seed is 14%, which is higher than the fraction for human food use (11%). About 2% (0.6 Tg) of global oats production is lost as waste. The highest loss rate is in Asia (6%) and South America (5%).

6.3.2. *Potential bioethanol production from oat*

The utilization of wasted oat grain could produce 225 ML of bioethanol, replacing 161 ML of gasoline when ethanol is used in E85. Dry milling of wasted oats could produce 1.5 dry kg of DDGS per kg of ethanol as a coproduct, replacing oat used for animal feed. More than a quarter million tons of oats (0.39 Tg) can be replaced by DDGS. The utilization of DDGS from oat dry milling to animal feed could produce another 160 ML of bioethanol. Therefore, wasted oat grain could produce 384 ML of bioethanol.

Complying with the 60% ground cover requirement, 11 Tg of oat straw is globally available, which could produce 2.8 GL of bioethanol. Furthermore,

Table 9
Regional potential bioethanol production from wasted oat grain and oat straw

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From oat straw	Total bioethanol (GL)	Gasoline equivalent (GL)
Africa	0.001	0.001	—	0.002	0.002
Asia	0.03	0.02	0.07	0.12	0.08
Europe	0.17	0.12	1.79	2.08	1.50
North America	0.004	0.003	0.73	0.74	0.53
Central America	0.0002	0.0002	0.009	0.01	0.007
Oceania	0.001	0.0004	0.12	0.12	0.09
South America	0.02	0.01	0.06	0.09	0.06
World	0.23	0.16	2.78	3.16	2.27

Table 10
Uses of rice grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	1.41	2.32	7.17	0.48	86.67	1.94
Asia	2.71	3.05	4.55	0.68	88.85	0.16
Europe	6.53	2.36	0.82	0.34	87.40	2.55
North America	0.00	3.18	12.15	12.31	66.78	5.57
Central America	0.73	1.23	4.11	3.89	89.66	0.38
Oceania	0.05	2.31	2.06	1.73	92.71	1.14
South America	2.05	2.75	8.35	3.00	83.18	0.66
World	2.62	2.99	4.82	0.88	88.35	0.33

lignin-rich fermentation residues could generate 3.5 TWh of electricity and 19.8 PJ of steam.

The utilization of wasted oat grain and oat straw could produce about 3.16 GL of bioethanol, replacing 2.27 GL of gasoline when bioethanol is used as E85 fuel. Europe could produce about 2 GL of bioethanol, which is more than half the potential bioethanol production from the utilization of wasted oat grain and oat stover. The regional potential bioethanol production from oat grain wastes and oat straw is shown in Table 9.

6.4. Rice

6.4.1. Global situation

The annual global production of dry rice is about 526 Tg. Asia is the primary production region with over 90% of global production and the largest harvested area for rice, 1.4 Mm^2. The rice yield in Asia is 3.5 dry Mg ha^{-1}, which is equal to the global average rice yield. The highest yield occurs in Australia with 7.8 Mg of dry rice per hectare.

Most rice (about 88% of global production) is used for human food. About 2.6% of global production is used for animal feed, but there is no rice used for animal feed in North America. About 4.8% of world rice production is lost as waste. About 22 Tg of dry rice in Asia is wasted, a quantity larger than the rice production of any other region. The highest fraction of wasted rice occurs in North America (12%). The uses of rice are illustrated in Table 10.

6.4.2. Potential bioethanol production from rice

If wasted rice could be fully utilized to produce bioethanol, then 12.3 GL of bioethanol could be produced, replacing 8.9 GL of gasoline. Rice dry milling

Table 11
Regional potential bioethanol production from wasted rice grain and rice straw

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From rice straw	Total bioethanol (GL)	Gasoline equivalent (GL) from wasted grain
Africa	0.52	0.19	5.86	6.57	4.72
Asia	10.5	3.87	186.8	201.2	144.5
Europe	0.01	0.004	1.10	1.11	0.80
North America	0.46	0.17	3.06	3.69	2.65
Central America	0.04	0.01	0.77	0.83	0.59
Oceania	0.01	0.004	0.47	0.49	0.35
South America	0.68	0.25	6.58	7.51	5.39
World	12.3	4.5	204.6	221.4	159

could produce 0.8 dry kg of DDGS per kg of ethanol as a coproduct, replacing rice grain used for animal feed. About 9.3 Tg of rice would be available due to the utilization of DDGS and could produce 4.5 GL of bioethanol. Therefore, wasted rice grain could produce 16.8 GL of bioethanol.

No rice straw must be left on the field to prevent erosion. Thus, rice straw could be fully utilized, resulting in 731 Tg of rice straw from which 205 GL of bioethanol could be produced. Furthermore, lignin-rich fermentation residue could generate 123 TWh of electricity and 708 PJ of steam.

Globally, wasted rice grain and rice straw could produce 221 GL of bioethanol, replacing 159 GL of gasoline (about 14.3% of global gasoline consumption). Asia has the greatest potential, 200 GL of ethanol from wasted rice grain and rice straw. The regional potential bioethanol production is shown in Table 11.

6.5. *Wheat*

6.5.1. *Global situation*

The annual global production of dry wheat is about 529 Tg. Asia (43%) and Europe (32%) are the primary production regions. North America is the third largest production region with 15% of global wheat production. Yield of wheat ranges from 1.7 to 4.1 dry Mg ha^{-1}. Global average yield is 2.4 dry Mg ha^{-1}. Like rice, China is the largest producer of wheat with about 18% of global production at an average yield of 3.4 dry Mg ha^{-1}. The second largest producer is India, where dry wheat production is 71 Tg (12%), and the yield is 2.4 dry Mg ha^{-1}. The highest yield occurs in Ireland, which produces 7.7 Mg of dry wheat per hectare.

Most wheat (71% of global production) is used for human food. About 17% of global production is used for animal feed, but the fraction of wheat used for animal feed in Europe, North America, and Oceania is over 25%. About 20 Tg of dry wheat (4% of global production) is lost as waste. About 10 Tg of dry wheat in Asia ends up in the waste stream. The uses of wheat are illustrated in Table 12.

6.5.2. *Potential bioethanol production from wheat*

The utilization of wasted wheat could produce 7.0 GL of bioethanol, replacing 5.0 GL of gasoline when ethanol is used in E85 for a midsize passenger vehicle. Wheat dry milling would produce 1.4 dry kg of DDGS per kg of ethanol as a coproduct, replacing wheat grain used for animal feed. About 10.8 Tg of wheat would be replaced by DDGS, resulting in 4.4 GL of bioethanol. Therefore, wasted wheat grain could produce 11.3 GL of bioethanol.

Under the 60% ground cover practice, about 354 Tg of wheat straw could be available globally and could produce 104 GL of bioethanol. Furthermore, lignin-rich fermentation residues could generate 122 TWh of electricity and 698 PJ of steam.

Table 12
Uses of wheat grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	4.68	2.26	5.71	0.18	85.87	1.30
Asia	4.34	5.46	4.50	0.64	84.31	0.74
Europe	38.78	8.13	2.44	1.60	46.72	2.33
North America	28.69	8.07	0.03	0.00	62.78	0.42
Central America	7.95	0.95	8.07	0.00	73.08	9.95
Oceania	42.00	8.29	4.02	3.07	28.19	14.44
South America	4.35	3.73	5.11	0.00	86.80	0.01
World	16.72	6.11	3.72	0.84	71.13	1.48

Table 13
Regional potential bioethanol production from wasted wheat grain and wheat straw

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From wheat straw	Total bioethanol (GL)	Gasoline equivalent (GL) from wasted grain
Africa	0.34	0.21	1.57	2.11	1.52
Asia	4.16	2.62	42.6	49.32	35.42
Europe	1.66	1.04	38.9	41.55	29.84
North America	0.01	0.006	14.7	14.68	10.54
Central America	0.10	0.06	0.82	0.98	0.70
Oceania	0.33	0.21	2.51	3.05	2.19
South America	0.37	0.23	2.87	3.47	2.49
World	6.95	4.38	103.8	115.2	82.71

Wasted wheat grain and wheat straw could produce globally 115 GL of bioethanol, replacing 83 GL of gasoline in an E85 midsize passenger vehicle, or about 7.5% of global gasoline consumption. Asia and Europe have the potential for producing over 40 GL of ethanol from wasted wheat grain and wheat straw. The regional potential bioethanol production is shown in Table 13.

6.6. Sorghum

6.6.1. Global situation

The annual global production of dry sorghum is about 53 Tg. Africa (33%) is the primary production region, and North America is the second largest production region (23% of global sorghum production). The yield of sorghum ranges from 0.8 to 3.7 dry Mg ha^{-1}. Global average yield is 1.2 dry Mg ha^{-1}. The US is the largest producer of sorghum (about 23% of global sorghum production) at a yield of 3.7 dry Mg ha^{-1}. The highest yield occurs in Israel and Jordan, which produce more than 10 Mg of dry sorghum per hectare.

The major uses of sorghum are animal feed (49%) and human food (40%). In Africa and Asia, over 60% of sorghum is used for human food. In the other regions, most sorghum is used for animal feed. There is no use of sorghum for human food in Europe and South America. About 3 Tg of dry sorghum (2 Tg in Africa), equivalent to 6% of sorghum production, is lost as waste. The uses of sorghum are illustrated in Table 14.

Table 14
Uses of sorghum grain

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	6.90	2.01	13.02	5.21	72.76	0.11
Asia	32.29	2.21	4.94	0.00	60.52	0.04
Europe	98.76	0.53	0.71	0.00	0.00	0.00
North America	86.80	0.30	0.00	9.88	3.03	0.00
Central America	94.85	0.38	2.19	0.00	2.58	0.00
Oceania	97.71	0.39	0.04	0.11	1.75	0.00
South America	95.09	0.69	4.21	0.00	0.00	0.00
World	49.10	1.39	6.11	3.20	40.15	0.05

Table 15
Regional potential bioethanol production from wasted sorghum grain and sorghum straw

	Potential bioethanol production (GL)				
	From wasted grain	From grain replaced by DDGS	From sorghum straw	Total bioethanol (GL)	Gasoline equivalent (GL)
Africa	1.01	0.55	—	1.55	1.12
Asia	0.24	0.13	—	0.37	0.27
Europe	0.002	0.001	0.10	0.10	0.071
North America	—	—	1.89	1.89	1.35
Central America	0.06	0.03	0.31	0.40	0.29
Oceania	0.0003	0.0001	0.09	0.09	0.06
South America	0.08	0.04	0.41	0.53	0.38
World	1.39	0.75	2.79	4.93	3.54

6.6.2. *Potential bioethanol production from sorghum*

The utilization of wasted sorghum grain could provide 1.4 GL of bioethanol, replacing 1 GL of gasoline. Sorghum dry milling could produce 1.2 dry kg of DDGS per kg of ethanol as a coproduct from waste sorghum. About 1.7 Tg of sorghum would be saved by DDGS, thereby producing another 752 ML of bioethanol. Therefore, the wasted sorghum grain could produce 2.1 GL of bioethanol.

For sorghum straw, 60% ground cover requires at least 2.7 Mg of crop residues per hectare [19]. Under these practices, 10.3 Tg of sorghum straw would be globally available and could produce 2.8 GL of bioethanol. Furthermore, lignin-rich fermentation residues could generate 3.7 TWh of electricity and 21 PJ of superheated steam.

Wasted sorghum grain and sorghum straw could produce 4.9 GL of bioethanol globally, replacing 3.5 GL of gasoline in an E85 midsize passenger vehicle, or about 0.3% of the global gasoline consumption. There is no bioethanol available from sorghum straw in Africa because the low yield requires that all straw be left in the field to conserve soil. The regional potential bioethanol production is shown in Table 15.

6.7. *Sugar cane*

6.7.1. *Global situation*

The annual global production of dry cut sugar cane (sugar content: 55% dry basis) is about 328 Tg. Asia (44%) is the primary production region, and South America is the second largest production region, producing 110 Tg of sugar cane (34%). The annual yield of dry sugar cane ranges from 14 to 22 Mg ha^{-1} with an average of 17 Mg ha^{-1}. Brazil is the largest single producer of sugar cane with about 27% of global production and a yield of 18 dry Mg ha^{-1}. The

Table 16
Uses of sugar cane

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	0.14	2.02	2.12	89.43	4.44	1.85
Asia	3.14	4.68	1.13	86.19	4.57	0.30
Europe	0.18	0.00	0.00	87.90	0.00	11.92
North America	0.00	5.37	0.00	94.62	0.00	0.00
Central America	1.80	0.25	1.06	95.40	0.05	1.45
Oceania	0.00	0.00	0.00	99.99	0.01	0.00
South America	0.98	0.00	0.68	97.83	0.27	0.24
World	1.91	2.35	0.97	91.88	2.40	0.48

Table 17
Regional potential bioethanol production from wasted sugar cane and sugar cane bagasse

	Potential bioethanol production (GL)			
	From wasted sugar cane	From bagasse	Total bioethanol (GL)	Gasoline equivalent (GL)
Africa	0.23	3.33	3.56	2.56
Asia	0.82	21.3	22.1	15.9
Europe	—	0.004	0.004	0.003
North America	—	1.31	1.31	0.94
Central America	0.18	5.46	5.64	4.05
Oceania	0.0001	1.84	1.84	1.32
South America	0.37	18.1	18.5	13.3
World	1.59	51.3	52.9	38.0

highest yield occurs in Peru, which produces more than 32 Mg of dry sugar cane per hectare.

Food manufacturing is the major use of sugar cane, consuming about 92% of sugar cane (a yield of 400 kg of sugar per dry ton of sugar cane). The fraction of other uses such as animal feed, human food, and so on, is less than 3% . About 3 Tg of dry sugar cane in the world becomes waste. However, there is no wasted sugar cane in North America, Oceania, and Europe. The uses of sugar cane are illustrated in Table 16.

6.7.2. *Potential bioethanol production from sugar cane*

Wasted sugar cane could produce 1.6 GL of bioethanol, replacing 1.1 GL of gasoline when ethanol is used in E85 fuel. Sugar cane bagasse is a coproduct in sugar cane food manufacture, and the yield of bagasse is about 0.6 dry kg per 1 dry kg of sugar cane used in food manufacture (producing about 120 Tg of sugar). Globally about 180 Tg of dry sugar cane bagasse is produced and can be utilized and could produce about 51 GL of bioethanol. Furthermore, lignin-rich fermentation residues from bagasse could generate 103 TWh of electricity and 593 PJ of steam.

Wasted sugar cane and sugar cane bagasse could produce globally about 53 GL of bioethanol, replacing 38 GL of gasoline in an E85 midsize passenger vehicle, or about 3.4% of the global gasoline consumption. Asia can produce about 22 GL of bioethanol. The regional potential bioethanol production is shown in Table 17.

7. Discussion

About 73.9 Tg out 2.1 Pg of dry grains plus cane sugar is lost during logistic processes: handling, storage, and transport. Six percent of total sorghum production is lost, the highest among any biomass considered in this study. In contrast, only 1% of total sugar cane production is wasted. Most wasted biomass comes from rice, corn, and wheat, as shown in Table 18. Asia has 45 Tg of wasted biomass. About 1.4 Pg out of 2.1 Pg of the major dry crop residues are available to produce bioethanol. The fraction of crop residue collected under the 60% ground cover practice varies with the region. In Africa, the fraction of most crop residues collectable is less than 30% because of low yields. In other regions, the collectable fraction of most crop residues is over 20%. Including dry sugar cane bagasse (181 Tg), the total dry lignocellulosic residue available is about 1.5 Pg.

About 491 GL of bioethanol might be produced from the wasted crops and their associated lignocellulosic raw materials, about 16 times higher than the current world ethanol production (31 GL).Crop residues are responsible for 90% of the total potential bioethanol production. The potential bioethanol production can replace 353 GL of gasoline, which is equivalent to 32% of the total gasoline worldwide consumption, when bioethanol is used in E85 for a midsize passenger vehicle.

Asia, which can produce 291 GL of bioethanol, is the largest potential producer of bioethanol. Rice straw (187 GL) is the most available feedstock in Asia. The next largest feedstocks in Asia are wheat straw (42.6 GL) and sugar cane bagasse (21.3 GL). The next largest potential producer of bioethanol in the world is Europe (69.2 GL), in which most bioethanol comes from wheat straw. Corn stover (38.4 GL) is the main feedstock for bioethanol in North America. These quantities are summarized in Table 19.

Furthermore, 458 TWh of electricity (about 3.6% of world electricity production) and 2.6 EJ of steam are also generated from burning lignin-rich fermentation residues, a coproduct of bioethanol made from crop residues and sugar cane bagasse. Most potential electricity and steam production comes from burning fermentation residues in the utilization of wheat straw. Electricity generated by these residues could reduce electricity produced from a fossil fuel burning power plant. Steam could be used within the ethanol plant or exported for a district heating system.

Table 18
Quantities of wasted crop and lignocellulosic biomass potentially available for bioethanol

	Africa	Asia	Europe	North America	Central America	Oceania	South America	Subtotal
Wasted crop (Tg)								
Corn	3.12	9.82	1.57	0.30	1.74	0.01	4.13	20.70
Barley	0.17	1.23	2.01	0.01	0.01	0.19	0.04	3.66
Oat	0.004	0.06	0.43	0.01	0.001	0.001	0.05	0.55
Rice	1.08	21.86	0.02	0.96	0.08	0.02	1.41	25.44
Wheat	0.83	10.28	4.09	0.02	0.24	0.82	0.91	17.20
Sorghum	2.27	0.54	0.004	0.00	0.13	0.001	0.18	3.12
Sugar cane	0.46	1.64	0.00	0.00	0.36	0.00	0.74	3.20
Subtotal	7.94	45.43	8.13	1.30	2.56	1.05	7.45	73.86
Lignocellulosic biomass (Tg)								
Corn stover	0.00	33.90	28.61	133.66	0.00	0.24	7.20	203.62
Barley straw	0.00	1.97	44.24	9.85	0.16	1.93	0.29	58.45
Oat straw	0.00	0.27	6.83	2.80	0.03	0.47	0.21	10.62
Rice straw	20.93	667.59	3.92	10.95	2.77	1.68	23.51	731.34
Wheat straw	5.34	145.20	132.59	50.05	2.79	8.57	9.80	354.35
Sorghum straw	0.00	0.00	0.35	6.97	1.16	0.32	1.52	10.32
Bagasse	11.73	74.88	0.01	4.62	19.23	6.49	63.77	180.73
Subtotal	38.00	923.82	216.56	218.90	26.14	19.70	106.30	1549.42

Table 19
Potential bioethanol production

	Africa	Asia	Europe	North America	Central America	Oceania	South America	Subtotal
From waste crop (GL)								
Corn	2.17	6.82	1.09	0.21	1.21	0.01	2.87	14.4
Barley	0.12	0.83	1.35	0.005	0.01	0.13	0.03	2.46
Oat	0.002	0.04	0.30	0.01	0.0004	0.001	0.03	0.38
Rice	0.71	14.4	0.02	0.63	0.05	0.02	0.93	16.8
Wheat	0.55	6.78	2.70	0.02	0.16	0.54	0.60	11.3
Sorghum	1.55	0.37	0.003	—	0.09	0.0004	0.12	2.14
Sugar cane	0.23	0.82	—	—	0.18	0.0001	0.37	1.59
Subtotal (A)	5.33	30.1	5.45	0.87	1.70	0.70	4.95	49.1
From lignocellulosic biomass (GL)								
Corn stover	—	9.75	8.23	38.4	—	0.07	2.07	58.6
Barley straw	—	0.61	13.7	3.06	0.05	0.60	0.09	18.1
Oat straw	—	0.07	1.79	0.73	0.009	0.12	0.06	2.78
Rice straw	5.86	186.8	1.10	3.06	0.77	0.47	6.58	204.6
Wheat straw	1.57	42.6	38.9	14.7	0.82	2.51	2.87	103.8
Sorghum straw	—	—	0.10	1.89	0.31	0.09	0.41	2.79
Bagasse	3.33	21.3	0.004	1.31	5.46	1.84	18.1	51.3
Subtotal (B)	10.8	261.0	63.8	63.2	7.42	5.70	30.2	442.0
Total (A+B)	16.1	291.1	69.2	64.0	9.12	6.39	35.1	491.1

8. Conclusions

Results indicate that rice straw is potentially the most favorable feedstock, and the next most favorable raw materials are wheat straw, corn stover, and sugar cane bagasse in terms of the quantity of biomass available. These four feedstocks can produce 418 GL of bioethanol. The most favorable area is Asia, which can produce 291 GL of bioethanol because of biomass availability.

In this study, only biomass availability is investigated to evaluate the feasibility of biomass utilization for bioethanol. The feasibility of biomass utilization for bioethanol and other biobased industrial products also includes factors such as which biomass to utilize and where to build a biorefinery. Decisions might be based on the following criteria, among others:

8.1. Biomass availability issue

Biomass availability is a primary factor. A favorable region for biobased industrial products should have surplus biomass and no problems with food security. Societal response to the utilization of biomass for biobased industrial products is also a factor. Some societies may be reluctant to use even waste crops for industrial products if they believe that somehow food resources are diminished. The biomass availability issue is a global matter because food security is a top global priority. However, when only the crop residues are considered, biomass availability tends to become a local matter.

8.2. Economic issue

Biobased products, including ethanol, must be made at competitive costs. Otherwise, there will be no market for the biobased products even though they are made from renewable resources. Economic factors, for example land availability, labor, taxation, utilities, crop processing costs, and transportation, especially the delivered cost of the biomass feedstock, are important. Hence, the economic issues are primarily local matters.

8.3. Environmental issue

One of the potential merits of biobased products is the utilization of renewable resources instead of non-renewable resources. However, specific crop production practices may reduce or even overwhelm this potential benefit. For example, a proper balance between the crop yield and the application rate of agrochemicals is needed. Other environmental issues in the agricultural operation, such as soil erosion, soil organic matter trends, water and groundwater use, should also be fully reviewed. These environmental issues tend to be local matters.

This study investigated the potential for utilization of wasted biomass and lignocellulosic feedstocks for bioethanol. The lignocellulosic feedstocks have much more favorable utilization potential for biobased industrial products because of their quantity and competitive price. Furthermore, lignocelluloses can generate electricity and steam, which can be used in a biorefinery and also exported into the power grid. Importantly, lignocellulosic feedstocks do not interfere with food security. However, facilitating the utilization of lignocellulosic materials requires tremendous efforts in achieving a high ethanol yield, establishing infrastructure for the collection system, increasing the thermal efficiency of generating electricity and steam, and so on.

Regarding the data quality of FAOSTAT, some nations may have a large gap between values in their national database and the data in FAOSTAT, as shown in Table 1. Technology for utilizing wasted crop, defined as crop lost in the distribution, as a raw material for biobased product will depend strongly on regional conditions, e.g., climate, storage facility, efficiency of transportation.

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