Economic Analysis For Sustainable Utilization of Ethanol Production Residues From Grain and Inedible Plant Wastes

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The global initiative to find alternative fuel sources to fossil fuels is an ongoing process. As such, bioethanol is used as a fuel blend with petrol. However, large number of solid wastes is produced from ethanol plants sourcing from grain and inedible plant wastes, for example, WDGS (wet distiller’s grain with soluble) and DDGS (dry distiller’s grain with soluble) produced from ethanol plants using corn. This study investigates alternative methods for using these co-products through combustion and anaerobic digestion. Process simulation and economic analysis were conducted using current market prices to evaluate the viability of the processes. Products in the form of energy are produced. Optimization of the corn ethanol plant was also explored for re-using the heat and electricity produced in those processes. The profits of combustion and anaerobic digestion were compared. It was found that these processes will supply more viable options to simply selling the grain as feed for livestock. The anaerobic digestion of WDGS to produce electricity scenario was found to have the biggest profit among the four scenarios which can bring the annual income of 14.1 million Australian dollar to the ethanol plant. An environmental analysis of the CO₂ emissions was also conducted. Using the Australian state emission factor, the amount of CO₂ offset through both combustion and anaerobic digestion can be seen. The anaerobic digestion of WDGS to supply heat to the plant was proved having the largest CO₂ abatement with the value of 0.58 kg-CO₂e/L-EtOH.

1. Introduction

In 2018, global energy consumption reached 13.86 billion tonnes oil equivalent, with an annual increase of 2.9% [1]. To minimise the effects of fossil fuels, bioethanol has been added to fuel as a quasi-renewable supplement, reducing carbon monoxide and unburned hydrocarbon emissions. A very recent study found that bioethanol can reduce petrol tailpipe carbon monoxide emissions by as much as 30% and tailpipe fine particle emissions by 50% [2]. As such, the whole world produced ca. 86.7 million tonnes of bioethanol as fuel additive in 2019 alone [3]. Beyond fuel, ethanol is also extensively used in many other usages such as alcoholic beverages.

The most widely used method of ethanol production is the fermentation process which is used to produce the bioethanol for fuel and alcoholic consumption. The products produced via this method include bioethanol, carbon dioxide, heat, and biomass residues with the ratio varying depending on the quality of feedstock and processes adopted. The source of bioethanol include corn, sorghum, wheat, sugarcane etc. [4, 5]. Among them, corn is one of the most popular resources for bioethanol production. According to a report of United States Department of Agriculture (USDA) [6], the ethanol derived from corn accounted for roughly 94% of all biofuel in the US by 2012. Corn kernels possess 70–72% of starch by weight. The ethanol formation process from corn is shown as [4]:

\[
(C_6H_{10}O_5)_n + nH_2O \xrightarrow{\text{Enzyme}} nC_6H_{12}O_6 \xrightarrow{\text{Yeast}} 2nC_2H_5OH + 2nCO_2
\]

R1

Comparable to the major bioethanol produced countries such as the United States and Brazil, Australia’s bioethanol industry is still in its first generation, sourced from wheat, sorghum and sugarcane. However, the second-generation bioethanol production derived from inedible plant wastes is also being considered due to the wide availability of biomass in Australia [7].

The two most common methods for bioethanol production from corn are dry grind and wet milling, accounting for 67 and 33%, respectively [8]. The flow diagram of the dry grind process is show in Figure 1 [4, 9].

The feedstock is cleaned during the pre-treatment stage, then crushed and milled before being sent to a liquefaction reactor in which the starch is partially hydrolysed to form dextrin and oligosaccharides. The liquefied starch along with the recycled water, yeast, and microbial glucoamylase enters the simultaneous saccharification and fermentation (SSF) stage. The oligosaccharides are further hydrolysed to glucose during the process of saccharification, followed by the fermentation process in which the glucose is decomposed to ethanol and carbon dioxide using yeast. The vapour stream predominantly containing ethanol and water is condensed and mixed with liquid stream, and then passes through two distillation columns for concentration and rectification. The stillage mixture is fed to the first evaporator train and then to a centrifuge to remove most of the water. The remaining wet solid mass is called wet distiller’s grain (WDG). The liquid removed by the centrifuge known as thin stillage is transferred to the second evaporator train. The syrup from the second evaporator combined with the WDG separated from the centrifuge is called wet distiller’s grain with soluble proteins (WDGS) which is further dried to dried distiller’s grain (DDG) [9].

Despite bioethanol-based fuels burning cleaner than fossil fuels, the co-products such as WDGS and DDGS can cause environmental impact. Only in 2015, the United States produced 41.8 million tonnes of corn ethanol, but also generated 27 million tonnes of solid residue - DDGS [10]. For the ethanol plants using inedible plant wastes as feedstocks, the production of solid co-products is also very high. For example, the mass of grape marc occupies between 11-25% of the crushed grapes for wine production [11].

Distiller's grain (DG) is commonly used as feed for livestock due to its high protein (approximately 27.8% by mass [12]) and vitamin contents. A rough approximation of the composition for the DDGS from corn is cellulose (9-16%), oil (8-11%), protein (25-30%) and the remaining, carbohydrates [13].

WDGS (approximately with 60–70% of moisture) only has a shelf life of 7-30 days, while DDGS (approximately with 10% of moisture) has almost indefinite shelf-life [14–16]. Thus, most corn ethanol plants dry WDGS to DDGS prior to distribution. However, the drying process is energy intensive, accounting for around 30-40% of the total energy requirement [17] and 50% of the natural gas usage in a typical dry mill ethanol plant [18]. This process increases the energy consumption significantly for the ethanol plant and largely reduces the energy efficiency.

In addition to the big energy penalty associated with the production of DDGS, the quality of solid co-product varies largely depending on the feedstocks used in ethanol plants. For example, the solid residues produced from the ethanol plant using inedible plant wastes as feedstocks has less value and may only be
used as a fertilizer or soil amendment. Thus, research into expanding the solid co-product uses is ongoing.

Cellulose recovery by extraction

Xu et al. [13] has investigated the extraction of the cellulose (approximately 9-16 wt% in DDGS) from DDGS as well as directly from corn kernels. The cellulose obtained has potential to be used as an absorbent due to its capability to absorb water up to nine times of its weight. Additionally, it could be used for paper, textile materials, films, fibres, and chemical filters.

Production of biochar and carbon materials

Another alternative method currently being researched by Wang et al. [10] is the conversion of DDGS to form 3-dimensional porous activated carbons using microwave-assisted chemical activation. Properties of activated carbon is eligible for removing dyes and heavy metals from liquids.

In a study carried out by our group [11], the pyrolysis of grape marc to produce biochar, bio-oil, and biogas was proposed and has shown big advantage in energy compensation for the wine industry in comparison with combustion.

Combustion

Combustion of DDGS or WDGS from corn is a path currently being explored. In the research done by Wang et al. [19], the corn derived ethanol production plant was theoretically modelled so that all steam required can be provided by the combustion of WDGS. The benefits of this process are to eliminate the requirement in drying WDGS and to replace the use of fossil fuels, hence reducing greenhouse gas emissions and optimising the overall production process. In our previous research [11], the technoeconomic analysis for the combustion of grape marc was also studied.

However, due to the lower content of carbon and higher content of oxygen in comparison to fossil fuels, solid co-products produced from ethanol industry has lower heating values. The low heating value can also cause flame stability issues. Moreover, the high moisture content can lead to ignition delay and consume more heat in moisture removal [20].

Anaerobic Digestion

One of the greatest issues faced when disposing of ethanol co-products is the high biochemical oxygen demand (BOD) with strict environmental laws in place. Anaerobic digestion of those solid co-products using microorganisms to produce biogas and liquid biofuels in the absence of oxygen is a sustainable and environmentally efficient method. The biogas produced typically consists of methane, carbon dioxide, ammonia, as well as hydrogen sulphide and water [21]. The methane produced from the digestion can be consumed locally inside the ethanol plant to reduce the consumption of fuel, with minimal clean up after its production.

In a study conducted by Belhadj et al. [22], the production of biogas was measured by assessing the stability of the process and the biodegradability of the bacteria applied. The stability of the reaction was optimal at a neutral pH range between 6.5 – 7.5. The production rate of biogas was dependant on the rate of reactions and degradability of the microorganisms during anaerobic digestion. The anaerobic digestion was generally carried out at the temperature between 35 - 55 ºC [23, 24].

The anaerobic digestion of stillage can be tracked back to 1950s, mainly focusing the treatment of wastewater. Until 1980s the energy recovery by biogas from stillage was integrated in a biofuel plant in Germany [25]. Ziganshin et al. [26] illustrated the digestion of DDGS and WDGS. Acetoclastic methanogens and hydrogenotrophic methanogens were proved the proper catalysts for the digestion. Alkan-Ozkaynak and Karthikeyan [27] directly used the thin stillage generated from corn-ethanol plants in anaerobic digestion to produce larger volumes of biogas. Baez-Smith [28] investigates the potential to anaerobically digest vinasse from sugarcane through a mathematical model. It described anaerobic digestion as a highly efficient treatment for reducing BOD in wastewater, as well as producing biogas. It was noted that substrates highly rich in lipids and easily degradable carbohydrates exhibit higher methane potential than lignocellulosic materials [29].

The current process of selling DDGS and WDGS as food for livestock might not be economically viable due to the fluctuating market value of the abundant product. The process of producing bioethanol from corn as well as from inedible plant wastes has potential to be optimised, through repurposing its co-products. Repurposing solid co-products such as WDGS and DDGS will encourage the growth of the bioethanol industry in countries such as Australia and deter reliance on non-renewable energy sources, fossil fuels.

This paper investigated alternative methods for utilising the co-products of the bioethanol industries such as DDGS and WDGS through combustion and anaerobic digestion. An economic analysis was conducted to assess the quality of products. To establish a basis of comparison, the value of selling the WDGS and DDGS as feed for livestock was also calculated. Optimisation of the corn ethanol process was explored through the recovery energy produced via combustion and anaerobic digestion of the biomass. This would ultimately improve the efficiency of the overall system and provide economic benefits.

2. Methodology

The comparison of anaerobic digestion and combustion processes was performed using the mass and energy balance capabilities of Aspen Plus (v10). The non-random two-liquid (NRTL) fluid package was selected in Aspen Plus when modelling. A techno-economic analysis was performed on the results from these simulations to assess the economic viability. An environmental analysis was also performed based on the modelling results.

2.1 Composition of the feedstocks
In this study, corn dry-grind ethanol by-products in the form of WDGS and DDGS as the model feedstocks (Table 1) were used to compare the energetic and economic balances within combustion and anaerobic digestion processes. It is noted that the dry base compositions of WDGS and DDGS are the same, but they have different moisture contents. Sulphur, nitrogen, and chlorine concentrations are negligible and hence omitted. All carbon and hydrogen will be fully oxidised to produce carbon dioxide and water, respectively, during the combustion. However, the processing via anaerobic digestion is more complicated and more detailed composition analysis is needed for the process simulation.

| Table 1: Lower heating values (LHV) and ultimate compositions of solid co-products generated from ethanol plants |
|--------------------------------------------------------------------------------------------------|
| Bagasse | Grape Marc | DDGS | WDG | Syrup | Corn Stover | WDGS/DDGS |
| LHV (MJ/kg) | 7.32 | 19.14 | 20.24 | 20.51 | 18.19 | 16.73 | 20.01 |
| Moisture (wt%) | 53.00 | 60.00 | 10.12 | 64.46 | 67.29 | 6.15 | 64.46/10.12 |
| Dry base composition (wt%) |  |  |  |  |  |  |  |
| C | 41.54 | 52.91 | 50.40 | 53.31 | 45.13 | 45.69 | 50.90 |
| H | 5.40 | 5.93 | 6.91 | 6.70 | 7.40 | 5.55 | 6.98 |
| O | 33.14 | 30.41 | 33.52 | 32.76 | 41.04 | 41.71 | 33.86 |
| N | 1.83 | 1.86 | 4.80 | 5.43 | 2.75 | 0.69 | 4.85 |
| S | 1.00 | 0.03 | 0.77 | 0.67 | 1.00 | 0.04 | 0.00 |
| Cl | - | 0.05 | 0.18 | 0.17 | 0.37 | 0.01 | 0.00 |
| Ash | 17.09 | 8.81 | 3.41 | 0.97 | 2.31 | 6.31 | 3.41 |
| Reference | [30] | [11] | [31] | This work |  |

The lower heating value of the dry matter was estimated by the contents of hydrogen and carbon with

\[
LHV = \sum_i LHV_i C_i \quad (1)
\]

where \(C_i\) is the mass content (wt%) and \(LHV_i\) is the lower heating value of the combustible component \(i\) in the biomass, \(i\) refers the element hydrogen or carbon. The lower heating values of hydrogen and carbon are 119.96 and 32.8 MJ/kg, respectively [32].

It is well known that the structural composition of biomass can be characterized with the ratio of cellulose, hemicellulose, and lignin. 90% of lignocellulosic and 80% of herbaceous biomass are composed by cellulose, hemicellulose, and lignin inside the lignocellulosic substrates [33]. Both hemicellulose and amorphous cellulose can be easily hydrolysed, while crystalline cellulose and lignin are resistant to bioconversion [34]. Therefore, the composition of cellulose, hemicellulose, and lignin still cannot give us enough information about how much biomass is anaerobically digestible.

For the application of pyrolysis or gasification, the biomass is normally divided into volatiles, fixed carbon, and ash, which is called proximate composition [35]. For anaerobic digestion, we are more interested in the digestible part, which overlaps but does not equal the volatiles content. Solvent extraction in addition of high-performance liquid chromatography (HPLC) analysis are applied in proximate analysis which supplies more meaningful information for anaerobic digestion. A Standard extraction procedure developed by the National Renewable Energy Laboratory (NREL) [35]. Kim et al. [35] further modified the procedure by doing the acid hydrolysis for the raw material. The composition of DDGS and WDGS from a variety of sources, as well as the values adopted in this study are listed in Table 2.

The proximate analysis groups the dry matter of DDGS and WDGS into crude protein, crude fat, carbohydrates, and ash. Carbohydrates contains crude fibre (9.73 wt% of DDGS in this study) and the remaining nitrogen-free extracts (39.00 wt% of DDGS in this study). Thus, the item of carbohydrates refers to all other nitrogen-free extracts except crude fibre.

Crude protein is the measurement of protein content, which can be digested into amino acids during the hydrolysis. The distribution of various amino acids was reported by Kim et al. [35], as shown in Table S1. The content of crude protein has a link with a so-called nitrogen factor as [35]:

\[
C_{\text{Crude Protein}} = NF \times C_{\text{Nitrogen}}
\]

where \(C_{\text{Crude Protein}}\) and \(C_{\text{Nitrogen}}\) are the mass contents of crude protein and the element nitrogen within the biomass, respectively, in wt%; NF represents the nitrogen factor with the value of 5.9 for DDGS and 5.4 for WDGS, depending on the resources of the biomass [35].

Crude fat, represented by the ether extract or the free lipid content, refers to the crude mixture of fat-soluble material present in a sample [36]. As the content of crude fat in DDGS and WDGS is small, we simply use oleic acid (C\(_{18}\)H\(_{34}\)O\(_2\)) to represent the average formula of the soluble part of crude fat.
Anaerobic Digestion of WDGS already applied to evaporate the moisture of WDGS down to approximately 10% in DDGS.

The combustion processes of DDGS and WDGS are modelled very similarly. However, in the combustion of DDGS (Figures 2a and S1a), the drying section (the yellow section in Figure S1b) are eliminated, and the feed with 10% moisture enters the combustor directly. However, it should be noted that extra energy is already applied to evaporate the moisture of WDGS down to approximately 10% in DDGS.

The combustion of WDGS involves drying the biomass to 10.12% of moisture before entering the combustor (Figures 2b and S1b) at 70 ºC [46, 47]. The recycled hot flue gas from the combustion is fed into a separator to separate the dry biomass and the exhaust. The air for combustion enters the reactor as a separate stream. Heat from the combustor is used to heat water in a boiler. Ash is removed from the stream and the hot flue gas is recycled back to the drier. Water entering the boiler is superheated to generate high pressured steam before entering the turbine. The resulting steam from the turbine then passes through a condenser cooling by ambient air. The turbine is assumed to operate at 70% isentropic efficiency.

The simulation was carried out with the following 4 scenarios: (1) combustion of DDGS to produce electricity, (2) combustion of WDGS to produce electricity, (3) anaerobic digestion of WDGS to produce heat, and (4) anaerobic digestion of WDGS to produce electricity.

### 2.2 Process description

Based on a report in 2013, the mean production capacity across all 214 existing ethanol plants in the United States is 107.5 million gallon (321 thousand tonnes) per year, equalling to a median plant capacity [44]. In our simulation, a plant with an annual ethanol production of 100 million gallons (equating to 378.5 million litres or 298.7 thousand tonnes) was applied. Using the information supplied by Urbanchuk [45], the amount of DDGS and WDGS produced annually was calculated and the following assumptions were made: (1) the plant with capability of 2.99 x 10^8 tonnes of ethanol production, equalling to 3.79 x 10^8 liter, (2) the plant is operated for 42 weeks per year, 7 days per week, and 24 hours per day, (3) 7.2 x 10^5 tonnes of WDGS with moisture content of 64.46% (assuming the same with WDG) is produced annually, (4) 2.8 x 10^5 tonnes of DDGS with moisture content of 10.12% is produced annually, and (5) it is assumed that the corn is already peeled and only the corn grain is to be used and there is no loss in grain mass during the drying process, other than the water removed.

The simulation was carried out with the following 4 scenarios: (1) combustion of DDGS to produce electricity, (2) combustion of WDGS to produce electricity, (3) anaerobic digestion of WDGS to produce heat, and (4) anaerobic digestion of WDGS to produce electricity.

### Combustion of WDGS and DDGS

Simplified block diagrams of the combustion processes of DDGS and WDGS can be seen in Figures 2a and b. More details can be found in Figures S1a and b in the Supplement. The combustion of those solid co-products can be simply expressed as [11]:

\[
C_aH_bO_c + \left( \frac{b}{4} - \frac{c}{2} \right)O_2 \rightarrow aCO_2 + \frac{b}{2}H_2O
\]

R2

The combustion of WDGS involves drying the biomass to 10.12% of moisture before entering the combustor (Figures 2b and S1b) at 70 ºC [46, 47]. The recycled hot flue gas from the combustion is fed into a separator to separate the dry biomass and the exhaust. The air for combustion enters the reactor as a separate stream. Heat from the combustor is used to heat water in a boiler. Ash is removed from the stream and the hot flue gas is recycled back to the drier. Water entering the boiler is superheated to generate high pressured steam before entering the turbine. The resulting steam from the turbine then passes through a condenser cooling by ambient air. The turbine is assumed to operate at 70% isentropic efficiency.

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### Anaerobic Digestion of WDGS

Carbohydrates except for crude fibre come in simple forms such as sugars and in complex forms such as starches and fibre including glucan, xylan, and arabinan etc. with the general formula of C_{6\_2}O_{5\_3} [39]. In this study, we assume that the carbohydrates include all nitrogen free extracts except for crude fibre, such as acid detergent fibre (ADF) and the extractives without the fat, with the average structure of dextrose (C_{6\_2}O_{5\_3}) after the water treatment.

Crude fibre refers to indigestible cellulose (60 – 80 wt%), pentosans, lignin (4 – 6 wt%), and other components of this type in biomass [40, 41]. In this study, we assume the crude fibre has the formula of basic unit of cellulose (C_{6\_2}O_{5\_3}) [42].

Fixed carbon is the solid carbon in biomass which remains in the char during pyrolysis [43].

Ash is composed of inorganic solid residua left after combustion, with the primary ingredients of silicon, aluminium, iron, and calcium oxides, and small amounts of magnesium, titanium, sodium, and potassium oxides, as well as the anthropogenic ash collected during harvest and handling [33, 43]. During the anaerobic digestion, ash refers the inorganic contents in biomass left after all proximate analysis processes.

### Table 2

| Reference  | Spiehs [37] | Belyea* [38] | NREL [35] | Kim [35] | Xu* [13] | This work | NREL [35] | Kim [35] | This work |
|------------|-------------|--------------|------------|---------|--------|---------|------------|---------|---------|
| Moisture   | 11.10       | -            | 11.20      | 11.10   | -      | 10.12   | 64.70      | 55.90   | 64.46   |
| Dry matter | 88.90       | -            | 88.80      | 88.90   | -      | 89.88   | 35.30      | 44.10   | 35.54   |
| Crude protein | 30.20       | 31.30        | 24.90      | 24.27   | 27.50  | 24.87   | 12.92      | 15.17   | 9.83    |
| Crude fat  | 10.90       | 11.90        | 11.60      | 12.89   | 9.50   | 13.21   | 3.39       | 4.81    | 5.22    |
| Carbohydrates | 33.20       | -            | 34.70      | 47.56   | -      | 39.00   | 13.73      | 23.24   | 15.42   |
| Crude fibre | 8.80        | 10.20        | -          | 4.50    | 1.65   | 3.06    | 0.71       | 0.88    | 1.21    |
| Ash        | 5.80        | 4.60         | 4.50       | 4.18    | 1.65   | 3.06    | 0.71       | 0.88    | 1.21    |

Note: * - average data
Generally, a no-biological step so called disintegration which converts biomass particulate to carbohydrate, protein and lipids is included before anaerobic digestion, which is not discussed in this work. Thus, anaerobic digestion involves four main processes: hydrolysis, acidogenesis, acetogenesis and methanogenesis [23, 48–50]. Each process involves different bacteria and microorganisms and different optimal conditions. The overall reaction can be expressed as [21]:

$$C_{a}H_{b}O_{c}N_{d} + \frac{4a - b - 2c + 3d}{4}H_{2}O \rightarrow \frac{4a + b - 2c - 3d}{8}CH_{4} + \frac{4a - b + 2c + 3d}{8}CO_{2} + dNH_{3}$$

For anaerobic digestion of biomass, a biodegradable factor is applied to calculate the maximum conversion [29, 51] with

$$f_{D} = \frac{COD_{D}}{COD_{T}}$$

where $f_{D}$ is the substrate biodegradable factor, COD$_{D}$ is the degradable chemical oxygen demand (mg/L) representing the specific methane yields, and COD$_{T}$ is the total chemical oxygen demand (mg/L).

Kim et al. [35] calculated the total digestible nutrients (TDN) in wt% of the DDGS by estimating the digestive factor of each part with

$$\text{TDN} = \sum f_{D,i}C_{i}$$

where $C_{i}$ is the mass content (wt%) and $f_{D,i}$ is the digestive factor of the component $i$ in the biomass, $i$ refers crude protein, crude fat, crude fibre, and other carbohydrates. The digestive factors for crude protein, crude fat, crude fibre, and other carbohydrates are set as 0.78, 0.90, 0.57, and 0.85, respectively, in this study.

The first stage of anaerobic digestion is hydrolysis. The purpose of hydrolysis is to covert the degradable portion of biomass (carbohydrates, proteins, and lipids) into free monomers, water soluble fragments including sugars, amino acids, and fatty acids. Pre-treatments such as oxidation, and alkali and acid addition for structural modification of lignocellulosic substrates are necessary to increase the enzymatic digestibility of cellulose [52]. During the hydrolysis, cellulose is converted into glucose and hemicellulose into both pentoses and hexoses. Hydrolysis is not discussed in detail in this paper. We just simply assume that all soluble COD within stillage and syrup is hydrolysable. The soluble COD contents in the stillage of different inedible resources were reported by Cesaro and Belgiorno [23]. The amino acid contents generated from the hydrolysation of WDGS was reported by Kim et al. [35].

The hydrolysates of cellulose and carbohydrates result in the production of sugar molecule, glucose, formulated as $C_{6}H_{12}O_{6}$ [53]. The hydrolysed products of crude protein are a series of amino acids with the average molecular formula of $C_{3}H_{7}O_{2}N$ in this study, a little bit heavier than $C_{3}H_{7}O_{2}N$ of alanine. The mass balance needs to be calculated by considering that the production of one mole of glucose or amino acid consumes one mole of water during the hydrolysis step. The consumed water is in the WDGS already. All possible involved components are listed in Table S1, and the stream composition of WDGS after hydrolysis in this simulation is listed in Table S2.

Acidogenesis is a biological reaction where simple monomers are further hydrolysed into volatile fatty acids and gas components by facultative anaerobic bacteria, while acetogenesis is a biological reaction where volatile fatty acids are degraded into acetic acid, carbon dioxide, and hydrogen [54] with presence of acetogenic bacteria which is an obligatory H$_{2}$ producer. During the acetogenesis, amino acids are mainly degraded through Stickland reactions in which one amino-acid acts as an electron donor and the other as an acceptor [55], for example,

$$CH_{3}CH(NH_{2})COOH + 2NH_{2}CH_{2}COOH + 2H_{2}O \rightarrow 3CH_{3}COOH + 3NH_{3} + CO_{2}$$

L-alanine glycine

Amino-acid can also be fermented with the presence of hydrogen-utilizing bacteria, a homo-acetogenic microorganism, for example,

$$NH_{2}CH_{2}COOH + H_{2} \rightarrow CH_{3}COOH + NH_{3}$$

However, Stickland reactions are the simplest and kinetically faster than uncoupled amino-acid reactions [56].

Methanogenesis is the last step in which acetates are further decomposed into methane and carbon dioxide, some CO$_{2}$ is hydrogenated into methane [56]:

$$CH_{3}COOH \rightarrow CH_{4} + CO_{2}$$

$$CO_{2} + 4H_{2} \rightarrow CH_{4} + 2H_{2}O$$

All hydrolysed organic compounds are assumed to be converted into methane by methanogens in this simulation.
There has been a lot of research published on the kinetics of anaerobic digestion by different groups [56–60]. However, the kinetic reaction rates and parameters vary a lot with the types of biomass and reactor, and reaction conditions. To simplify the simulation, yield-based reactors were applied by assuming all dissolved monomers and small molecules can be fully converted to produce biogas. The solubilities of the proximate components equalise the digestive factors showed in equation 4. The only exception is the conversion of hydrogen in Reaction 7 which was set as 93%. These processes are modelled with Aspen Plus (v10) using specific amino acid reactions sourcing from the model applied by Serrano [56], including 45 compounds (as shown in Table S1). The simplified reactions applied in this simulation were listed in Table S3. It is notable that the reactions applied in this study are only for the simulation purpose to meet the overall mass balance, the actual reactions may occur in different ways as discussed above.

Figures 2c and d depict simplified block diagrams of the anaerobic digestion process in two approaches: the biogas is simply burnt to produce heat (Figure 2c) or is used to drive a steam turbine to produce electricity (Figure 2d). More detailed diagrams are shown in Figures S1c and d in the Supplement. The anaerobic digester was modelled as a two-stage plant with a flash vapouriser. The first digester conditions are set for acidogenesis to undergo optimally at 55 °C and atmosphere pressure, and the second digester for acetogenesis and methanation also at the same temperature and pressure [56]. Biogas and waste are separated from the flash unit. The biogas produced is cooled down to further reduce the moisture content and then is combusted producing heat (Scenario 3) or electricity (Scenario 4), and the waste is centrifuged to separate the liquid with the solid wastes.

### 2.3 Economic Analysis

An economic analysis is conducted to gauge the feasibility of their real-world applications. Capital costs are calculated using the equipment costs from reference values. The exponential method is used to estimate the equipment costs, which is based on existing costs and data from credible sources like a company or published data to establish a capacity-ratio exponent:

$$\text{Cost}_2 = \text{Cost}_1 \left( \frac{q_2}{q_1} \right)^a$$

where $\text{Cost}_1$ is the cost of equipment at a given size capacity of $q_1$, the value of the exponent $a$ depends on the type of the equipment. The chemical engineering plant cost index (CEPCI) value is considered which accounts for inflation over the given period [61, 62]:

$$\text{Cost}_A = \text{Cost}_B \times \frac{\text{CEPCI}_A}{\text{CEPCI}_B}$$

where $\text{Cost}_A$ and $\text{CEPCI}_A$ are the cost and the chemical engineering plant cost index at the year $t$, respectively. In this study, we converted the cost up to end of 2019 to avoid the effect of covid-19 in 2020.

The Lang factor ($L$) is used to estimate the installation costs of the plant on different locations. For example, $L = 1.25$ is the location factor in Melbourne, Australia relative to the US Gulf Coast Basis (USGC) [63].

When calculating the total cost of the plant, the following assumptions were made: (1) the non-variable operating costs equates to 5% of the total capital costs, (2) the investment term is 10 years, (3) the operation term is 10 years, (4) construction is undergone in 1 year, (5) interest rate is 5% of capital costs, and (6) depreciation is 5% of capital costs.

Selling the WDGS and DDGS at market value at the end of 2019 was used in comparation with the profits made from combustion and anaerobic digestion. The market price of DDGS from Kansas sold by United BioEnergy on 3rd September 2020 is 140 US$/tonne [64]. In this study we adopt 191.78 A$/tonne by considering the currency exchange rate at 1 A$ = 0.73 US$ on 4th September 2020. The market price of WDGS on the same day is 45 US$/tonne, equivalent to 61.64 A$/tonne. The average electricity price was 0.29 A$/kWh in Australia in March 2020 [65]. The natural gas price on 22 February 2021 is 2.99 US$/MMBtu [66], which is 0.14 A$/Nm$^3$ (N refers to the value at the standard conditions at 25 °C and atmospheric pressure). The natural gas is assumed to be consumed for heating requirements in the corn ethanol process, which is 220 btu/bushel-corn (equivalent to 9.14 MJ/t-corn) [67] where btu refers British thermal unit. Drying of WDGS to DDGS is also required eternal heat generated by combustion of natural gas.

For the depreciation of the plant, a straight depreciation line was applied [68]. The annual loan payment was calculated as [69]:

$$LP = \frac{LA}{DF}$$

with

$$DF = \frac{(1 + r)^n - 1}{r(1 + r)^n}$$

where $LP$ is the loan payment (A$), $LA$ is the loan amount (A$), and $DF$ is the discount factor, $r$ is the interest rate, and $n$ is the loan life in years.

### 2.4 Environmental Analysis
The environmental analysis was conducted accounting for the CO\textsubscript{2} emissions from the digestion processes as well as in comparison of combustion. The CO\textsubscript{2} offsets by combustion and anaerobic digestion are calculated.

### 3. Results And Discussions

The products from the combustion and anaerobic models are energy in the form of electricity or heat. The processes were modelled with the scale for the annual DDGS production of \(2.8 \times 10^5\) tonnes and WDGS of \(7.2 \times 10^5\) tonnes by assuming the plant is continuously operated for 42 weeks per year, in responding to the flow rates of DDGS and WDGS at 40.3 and 102.0 tonnes/hour, respectively, in which the dry mass equals 36.3 tonnes/hour.

#### 3.1 Combustion of WDGS and DDGS

When modelling the combustion processes, the air was input with an excess of 25% of the stoichiometric requirement to ensure full combustion.

The combustion of DDGS yields a greater electricity output than the combustion of WDGS: 33.8 and 27.2 MW for combustion of DDGS and WDGS after offsetting the electricity consumption of the pump, as seen in Table 3. However, considering the large heat requirement for drying (153.7 MW) in the production of DDGS, using WDGS is beneficial as the waste heat of the combustion can be integrated into the drying of WDGS. In this simulation, the temperature of the drier was controlled at 75 °C. Conversely, as the combustion of DDGS does not require a drier, the flue gas is discharged to the atmosphere at 110 °C.

#### 3.2 Anaerobic digestion of WDGS

As anaerobic digestion requires the biomass to be wet, WDGS is chosen as the feed, skipping the energetic costly drying process. The reactors are set to be operated at 55 °C. The yield of biogas is 1127.6 Nm\textsuperscript{3} per tonne of dry mass by converting the flow rate of biogas into volume under standard conditions. As the biogas is a mixture of methane, CO\textsubscript{2} and hydrogen, and small amount of NH\textsubscript{3}, H\textsubscript{2}S etc. (Table S4), the purification system will be complex which has been well studied [70–72].

The biogas can be combusted to generate heat or electricity. The produced heat can be recycled back to the ethanol plant to offset the natural gas requirement. In addition of this, the biogas could also be used for (1) the production of synthetic methane via CO\textsubscript{2} methanation reaction [73, 74]; (2) the production of renewable hydrogen via bi-reforming [75] followed by water-gas shift reaction [49, 76]; and (3) biofuel production via reverse water-gas shift reaction [77] followed by fuel synthesis[48, 78], depending on the need of market and the scale of plant.

As seen from the energy balance in Table 3, biogas combustion can generate 28.95 MW of electricity, even slightly larger than the electricity output of the direct combustion of WDGS. It is because the anaerobic digestion does not need the drying step. As we know, the electricity generation requires a higher capital cost as the turbine and boiler are the two most expensive items. Moreover, the energy loss during the energy conversion makes the process less efficient. The biogas can be directly burnt to generate 159 MW of heat. By considering the lower heating value of methane is 50 MJ/kg [32], the plant can save about \(8.08 \times 10^4\) tonne of natural gas every year, which is \(1.21 \times 10^8\) m\textsuperscript{3}/year. For a small size of ethanol plant, this scenario might be more affordable.
Table 3
Simulation results for 4 scenarios

| Scenario | 1      | 2      | 3      | 4      |
|----------|--------|--------|--------|--------|
| Feed     | DDGS   | WDGS   | WDGS   |        |
| Process  | Combustion | Anaerobic digestion |        |        |
| Energy produced | Electricity | Heat | Electricity |        |
| Flow rate (tonne/hour) | 40.35 | 102.04 | 102.04 | 102.04 |
| Electricity generated (MW) | 34.07 | 27.4 | - | 28.95 |
| Electricity for Pump (MW) | 0.23 | 0.19 | - | 0.15 |
| Heat generated (MW) | -153.73 | - | 158.99 | - |
| Natural gas offset (Mm$^3$/year) | -116.84 | - | 120.84 | - |
| CO$_2$e (tonne/year) | -1.97$\times10^4$ | -1.88$\times10^5$ | -2.22$\times10^5$ | -1.99$\times10^5$ |
| Normalised CO$_2$e (kg/L-EtOH) | -0.05 | -0.49 | -0.58 | -0.52 |
| CAPEX (10$^6$ A$^\$$) | 1.40* | 1.63 | 2.22 | 2.72 |
| Cash flow (10$^6$ A$^\$$/year) |        |        |        |        |
| Loan payment | -0.18 | -0.21 | -0.29 | -0.35 |
| Non-variable OPEX | -0.07 | -0.08 | -0.11 | -0.14 |
| Depreciation | -0.14 | -0.16 | -0.22 | -0.27 |
| DDGS/WDGS | -54.6 | -44.38 | -44.38 | -44.38 |
| Natural gas | -16.93 | 0 | 17.51 | 0 |
| Electricity | 69.71 | 55.68 | 0 | 59.24 |
| Total | -2.21 | 10.84 | -27.49 | 14.10 |

*The CAPEX does not include the drying facility to produce DDGS

The waste sludge from the digester has little value and is centrifuged prior to disposal. The non-digestible solid waste separated by the centrifugation still maintains enough nutrition which can be applied as the compost and fertiliser after proper neutralization [79].

3.3 Economic Analysis

The capital expenditure (CAPEX) and main operating expenditure (OPEX) are also listed in Table 3 and plotted in Figure 3, in which the positive values represent the cash flowing in and the negative ones refer the cash flowing out. The OPEX includes the production and non-manufacturing costs. The production cost can be decomposed into variable and fixed costs, in which the variable cost includes raw material and utility consumptions, and the fixed cost can be further divided into the labour cost, plant overheads, the maintenance, the insurance, and the property tax. The non-manufacturing cost covers the corporate administration and selling expenses, and the investment in the research and the development, etc. [77]. Here we just simply separate the variable cost out of other operating costs. The main cash flow segments of all simulated scenarios are shown in Figure 3.

As seen in Table 3, the estimated capital costs for the combustions of WDGS and DDGS are 1.63 and 1.40 million Australian dollars, respectively. The difference is due to the omission of the dryer in the combustion of DDGS. The capital costs for the anaerobic digestion process are higher than that for combustion, which are 2.22 and 2.72 million Australian dollars for heat and electricity production, respectively. Waste handling and treatment for digestion are also included in the operating cost. The cost of microorganisms was not accounted in this simulation. The price of the anaerobic digester is estimated from plants in the United States used in the digestion of animal manure [80] with the similar size ranges of the digesters.

The electricity value produced from the combustion of DDGS (Scenario 1) is higher than those produced from the combustion (Scenario 2) and anaerobic digestion (Scenario 4) of WDGS. However, the negative natural gas offset for the combustion of DDGS describes the additional energy costs consumed in the dryer to produce DDGS. Thus, a third of the natural gas requirement in the corn ethanol plant can be eliminated by direct processing WGDS in which the heat transferred from the recycled flue gas can offset the heat requirement for drying.

Like combustion process of WDGS, the natural gas value shown in Table 3 and Figure 3 depicts the value of natural gas offset by using the heat produced from the combustion of the biogas. As the current natural gas price is at a low level, The Scenario 3 is not profitable. The efficiency of investment for the anaerobic digestion of WDGS to produce electricity (Scenario 4) is the highest among the four simulated scenarios. This scenario can bring 14.10 million Australian dollars of income per year to the plant, equalling to 3.72 ¢/L-EtOH.

To optimise the corn ethanol process, it is assumed that electricity produced from combustion is used in the corn ethanol plant, which offsets portion of the electricity requirement. It is also possible to sell the electricity back to the grid. In addition, the solid wastes could be used as the soil mediation purpose after neutralisation. Moreover, gas combustor will be more efficient than solid combustor.
3.4 Feasibility and sensibility analyses

It is clearly demonstrated from Table 3 and Figure 3 that the profit of the plant is mainly determined by the prices of electricity, natural gas, DDGS, and WDGS. The OPEX is affected by the prices of various parameters such as the feed cost, utility cost, product price, labour cost, as well as the scale of the plant [77]. To perform the sensitivity analysis, we only focus on the feed and utility costs within the range of $k_i (1 \pm 20\%)$ where $k_i$ refers to individual parameters. Then the OPEX changes relative to the base value are calculated as:

$$\Delta \text{OPEX} = \text{OPEX}_{k_i (1 \pm 20\%)} - \text{OPEX}_{k_i}$$

which are plotted in Figure 4.

The prices of electricity and natural gas play a critical role in the sustainable utilization of ethanol production residues from grain and inedible plant wastes. The electricity values generated from all processes except Scenario 3 are quite similar. When the price of electricity increases, it is expected that all electricity production scenarios will have more profit. The price of natural gas has opposite effects to Scenarios 1 and 3. If the price of natural gas increases, the negative gain of Scenario 3 may drop down to an acceptable range and even will be overturned into positive when the price reaches 0.37 A$/m^3$ as shown in Figure 5. Moreover, when the price of natural gas reaches 0.48 A$/m^3$, Scenario 3 will take turns Scenario 4 becoming the most profitable choice. In this case, drying WDGS to make DDGS will be more costly. The prices of feedstocks (DDGS and WDGS) have similar effects to all scenarios. In the extreme case, where the DDGS and WDGS have good market, they would be sold directly.

3.5 Environmental Analysis

The processing of biomass is a carbon-neutral process. The production of electricity or fuel offset from the processing of biomass will result in a reduction of energy input of the ethanol plant, and therefore lead a negative carbon emission to the environment. From a report issued by Australian government in 2020 [81], the emission intensity of electricity production in Victoria was found to be 0.98 kg-CO$\text{$_2$/kWh}$ (e stands for emission). Thus, from the energy production and fuel offset, the CO$\text{$_2$}$ equivalent emissions for the combustion and digestion processes can be easily calculated.

As expected, all processes have positive benefit to the reduction of carbon footprint (Table 3). The combustion of DDGS has the least advantage from the view of CO$\text{$_2$}$ emission due to the significant energy penalty during drying WDGS. All other three scenarios have similar effect on carbon emissions with the anaerobic digestion to produce heat (Scenario 3) as the best due to the large offset in natural gas. The CO$\text{$_2$}$ abatement from the amount of CO$\text{$_2$}$ sequestered by the anaerobic digestion process is more than the direct combustion of DDGS and WDGS as the solid waste rich of carbon produced from the anaerobic digestion can be disposed without direct CO$\text{$_2$}$ emission.

4. Conclusion

This project aims to research alternative methods of sustainably utilising these co-products in an environmentally and economically viable manner. WDGS and DDGS were used as examples to perform the simulation in this study. The sustainability of bioethanol production from grain and inedible plant wastes can be increased and potentially the ethanol production process can also be improved by introducing the processes investigated in this study.

The two alternative methods, combustion of WDGS and DDGS and anaerobic digestion of WDGS, are modelled with Aspen Plus software. The products yielded from these processes were energies in the forms of electricity and heat. From the results, a huge difference between the combustions of DDGS and DDGS was shown. By incorporating the drying process into the combustion process of WDGS without additional energy input, it offsets the energy requirement for current drying process in corn ethanol plant. Furthermore, the electricity generation reduces the reliance on the electricity grid. By investigating the combustion and anaerobic digestion of both WDGS and DDGS, it caters to a wider range of existing corn ethanol plants. Although with the current prices of WDGS and DDGS, electricity, and natural gas, it is still economically beneficial to maintain current processes to sell WDGS and DDGS as feeds for livestock, the processes investigated in this study are still seen to be more valuable. These will supply more attractive options based on the market prices of those variable operating expenditures. The alternative method of anaerobic digestion to produce electricity has environmental benefits, profitable and is more energy efficient. Moreover, this process also has potentials as a pathway to other products such as bio-hydrogen, biomethane, and biofuel. The solid wastes produced from the anaerobic digestion can also be used in soil mediation purpose.

An economic analysis was conducted which accounted for estimates of capital, operating, and waste handling costs, where necessary. The products were quantified using current market values for industrial electricity and natural gas in Australian dollars. The combustion of WDGS offset both heat and electricity from the corn ethanol process and hence was the more economically lucrative process from the combustion of DDGS with the profit of 10.84 million Australian dollars per year. The large amount of heat requirement during the production of DDGS makes the combustion of DDGS non-profitable on the current market. The anaerobic digestion of WDGS to produce heat is even worse. The anaerobic digestion of WDGS to produce electricity scenario generates the biggest profit among the four scenarios which can bring the annual income of 14.10 million Australian dollar to the ethanol plant, which equals to 3.72 c/L-ETHOH.

An environmental assessment of the CO$\text{$_2$}$ emissions was also conducted. As expected, the combustion of DDGS has a significantly higher CO$\text{$_2$}$ equivalent emission compared to other scenarios, while the anaerobic digestion of WDGS to supply heat to the plant has the largest CO$\text{$_2$}$ abatement with the value of 0.58 kg-CO$\text{$_2$/L-ETHOH}$.

Declarations
References

1. BP, BP Statistical Review of World Energy. 2019. p. 1 - 64
2. United Petroleum. Facts about Ethanol. 2020; Available from: https://www.unitedpetroleum.com.au/fuel/ethanol-production/
3. Renewable Fuels, A., 2019 ETHANOL INDUSTRY OUTLOOK. 2020. p. 1 - 36
4. Wiedemann, S.G., et al., Review of grain-based ethanol production effects on Australian livestock industries. 2008, Meat & Livestock Australia p. 1 - 148
5. Rabelo, S.C., et al.: Production of bioethanol, methane and heat from sugarcane bagasse in a biorefinery concept. Biore. Technol. 102(17), 7887–7895 (2011)
6. Capehart, T. U.S. Bioenergy Statistics. Economic Research Service 2020 April 21, 2020; Available from: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/
7. Puri, M., Abraham, R.E., Barrow, C.J.: Biofuel production: Prospects, challenges and feedstock in Australia. Renew. Sustain. Energy Rev. 16(8), 6022–6031 (2012)
8. Bothast, R.J., Schlicher, M.A.: Biotechnological processes for conversion of corn into ethanol. Appl. Microbiol. Biotechnol. 67(1), 19–25 (2005)
9. Quintero, J.A., et al.: Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case. Energy 33(3), 385–399 (2008)
10. Wang, Y., et al.: Development of Low-Cost DDGS-Based Activated Carbons and Their Applications in Environmental Remediation and High-Performance Electrodes for Supercapacitors. J. Polym. Environ. 23(4), 595–605 (2015)
11. Zhang, N., et al., Sustainable options for the utilization of solid residues from wine production. Waste Management, 2017. 60(Supplement C): p. 173-183
12. Kwiatkowski, J.R., et al.: Modeling the process and costs of fuel ethanol production by the corn dry-grind process. Ind. Crops Prod. 23(3), 288–296 (2006)
13. Xu, W., Reddy, N., Yang, Y.: Extraction, characterization and potential applications of cellulose in corn kernels and Distillers' dried grains with solubles (DDGS). Carbohydr. Polym. 76(4), 521–527 (2009)
14. Baskett, J., et al., Storage and Handling of High Moisture and Handling of High Moisture Co-Products from Ethanol on Ethanol Production in Beef Operations—Beef Producer: Study in Animal Industry Report. 2009, Iowa State University. p. 1 - 7
15. Rutherford, B.: Low-Cost Storage Of Wet Distillers Grains. Beef 2011 May 06, 2011, Available from: https://www.beefmagazine.com/cowcalfweekly/0506-low-cost-storage-distillers-grain
16. Zimmerman, M. DDGS 101: The Basics. 2020; Available from: https://www.mnbiofuels.org/media-mba/blog/item/1378-ddgs-101-the-basics
17. Braid, A., Biofuel co-products as livestock feed: a report for the Rural Industries Research and Development Corporation / by Andrew Braid. RIRDC publication; no. 07/175., ed. R. Rural Industries, et al. 2007, Barton, A.C.T: Rural Industries Research and Development Corporation
18. Nyendu, G.C.: Storability of modified wet distillers grains with solubles, in Agricultural Engineering and Biorenewable Resources and Technology 2011, Iowa State University: Ames, Iowa. p. 1 - 122
19. Wang, M., Wu, M., Huo, H.: Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environmental Research Letters 2(2), 024001 (2007)
20. Demirbas, A.: Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog. Energy Combust. Sci. 31(2), 171–192 (2005)
21. Kiatskitipong, W., Wongsuchoto, P., Pavasant, P.: Life cycle assessment of bagasse waste management options. Waste Manag 29(5), 1628–1633 (2009)
22. Belhadj, S., et al.: The biogas production from mesophilic anaerobic digestion of vinasse. IOSR Journal Of Environmental Science, Toxicology And Food Waste Management, 2017.
23. Cesaro, A., Belgiorno, V.: Combined Biogas and Bioethanol Production: Opportunities and Challenges for Industrial Application. Energies 8(8), 8121–8144 (2015)
24. Rajendran, K., et al., Chapter 5 - Influential Aspects in Waste Management Practices, Sustainable Resource Recovery and Zero Waste Approaches, M.J. Tahirzadeh, et al., Editors. 2019, Elsevier. pp. 65–78
25. Drosg, B., et al.: Anaerobic digestion of stillage fractions – estimation of the potential for energy recovery in bioethanol plants. Water Sci. Technol. 67(3), 494–505 (2013)
26. Ziganshin, A.M., et al.: Bacteria and archaea involved in anaerobic digestion of distillers grains with solubles. Appl. Microbiol. Biotechnol. 89(6), 2039–2052 (2011)
27. Alkan-Ozkaynak, A., Karthikeyan, K.G.: Anaerobic digestion of thin stillage for energy recovery and water reuse in corn-ethanol plants. Biore. Technol. 102(21), 9891–9896 (2011)
28. Baez-Smith, C. Anaerobic Digestion of Vinasse for the Production Of Methane in the Sugar Cane Distillery. in Sugar Processing Research Conference. 2006. Águas de São Pedro, S. P, Brazil
29. Labatut, R.A., Angenent, L.T., Scott, N.R.: Biochemical methane potential and biodegradability of complex organic substrates. Biore. Technol. 102(3), 2255–2264 (2011)
30. Janghathaikul, D., Gheeewala, S.H.: Environmental Assessment of Power Generation From Bagasse at a Sugar Factory in Thailand. International Energy Journal 6(1), 357–366 (2005)
31. Morey, R.V., et al.: Fuel Properties of Biomass Feed Streams at Ethanol Plants. Appl. Eng. Agric. 25(1), 57–64 (2009)
32. Wikipedia. Heat of combustion. 2021 9 January 2021; Available from: https://en.wikipedia.org/wiki/Heat_of_combustion
33. Williams, C.L., Emerson, R.M., Tumulu, J.S., Biomass Compositional Analysis for Conversion to Renewable Fuels and Chemicals, in Biomass Volume Estimation and Valorization for Energy, J.S. Tumulu, Editor. 2017, IntechOpen
34. Holloway, W.D., Tasman-Jones, C., Lee, S.P.: Digestion of certain fractions of dietary fiber in humans. The American Journal of Clinical Nutrition 31(6), 927–930 (1978)
35. Kim, Y., et al.: Composition of corn dry-grind ethanol by-products: DDGS, wet cake, and thin stillage. Biorens. Technol. 99(12), 5165–5176 (2008)
36. Food Science. Crude Fat. 2008 April 16, 2008; Available from: https://www.foodscience-avenue.com/2008/04/crude-fat.html#~:text=Crude%20fat%20is%20a%20term%20of%20fat%20in%20products
37. Spiehs, M.J., Whitney, M.H., Shuron, G.C.: Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. J. Anim. Sci. 80(10), 2639–2645 (2002)
38. Belyea, R.L., Rausch, K.D., Tumbleson, M.E.: Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. Biorens. Technol. 94(3), 293–298 (2004)
39. Davidson, E.A.: Carbohydrate. Encyclopaedia Britannica (2020)
40. Biocyclopedia. Methodology for Carbohydrates - Estimation of crude fiber. Plant Lab Protocols; Available from: https://biocyclopedia.com/index/plant_protocols/carbohydrates/Estimation_of_crude_fiber.php
41. Food Science. Crude Fiber. 2008 April 24, 2008; Available from: https://www.foodscience-avenue.com/2008/04/crude-fiber.html
42. Heinze, T.: Cellulose: Structure and Properties, in Cellulose Chemistry and Properties: Fibers, Nanocelluloses and Advanced Materials, O.J. Rojas, Editor. 2016, Springer International Publishing: Cham. p. 1-52
43. Basu, P.: Chapter 3 - Biomass Characteristics, in Biomass Gasification, Pyrolysis and Torrefaction (Third Edition), P. Basu, Editor. 2018, Academic Press. p. 49-91
44. Hoagland, K.: Comparing Plant Capacities of U.S. Ethanol & Biodiesel Industries, in Biomass. BBI International (2013)
45. Urbanchuk, J.: Current State of the U.S. Ethanol Industry 2010, Cardno ENTRIX. p. 1 - 48
46. Monceaux, D.A., Kuehner, D.: Dryhouse technologies and DDGS production, in The Alcohol Textbook, pp. 303–322. Lallemand Ethanol Technology and Nottingham University Press (2009)
47. ZJN, H.E.S.-T.C. Distiller's Grains/DDGS Drying. 2020; Available from: http://www.zjndrying.com/product/Distillers-Grains-Drying.html?gclid=EAIaIQobChMl68Pf5sSsr7QVjzJrCh3fKgsEAYAVASAAEjIPD_BwE
48. Beschkov, V., Biogas, Biodiesel and Bioethanol as Multifunctional Renewable Fuels and Raw Materials, in Frontiers in Bioenergy and Biofuels, E. Jacob-Lopes and L.Q. Zepka, Editors. 2017, IntechOpen
49. Khan, I.: Waste to biogas through anaerobic digestion: Hydrogen production potential in the developing world - A case of Bangladesh. Int. J. Hydrogen Energy 45(32), 15951–15962 (2020)
50. Cañote, S.J.B., et al.: Energy and Economic Evaluation of the Production of Biogas from Anaerobic and Aerobic Sludge in Brazil. Waste Biomass Valoriz. 8(2), 947–969 (2021)
51. Agler, M.T., et al., Thermophilic Anaerobic Digestion to Increase the Net Energy Balance of Corn Grain Ethanol. Environmental Science & Technology, 2008. 42(17): pp. 6723–6729
52. Cesaro, A., Belgiorno, V.: Pretreatment methods to improve anaerobic biodegradability of organic municipal solid waste fractions. Chem. Eng. J. 240, 24–37 (2014)
53. Huang, Y.-B., Fu, Y.: Hydrolysis of cellulose to glucose by solid acid catalysts. Green Chem. 15(5), 1095–1111 (2013)
54. Xu, F., et al., Anaerobic Digestion of Food Waste for Bioenergy Production, Encyclopedia of Food Security and Sustainability, P. Ferranti, E.M. Berry, and J.R. Anderson, Editors. 2019, Elsevier: Oxford. pp. 530–537
55. Nisman, B.: The Stickland Reaction. Microbiol. Mol. Biol. Rev. 18(1), 16–37 (1954)
56. Serrano, R.P., Biogas Process Simulation using Aspen Plus, in Department of Chemical Engineering, Biotechnology and Environmental Technology. 2011, Syddansk Universitet. p. 1-88
57. Mähnert, P., Linke, B.: Kinetic study of biogas production from energy crops and animal waste slurry: Effect of organic loading rate and reactor size. Environ. Technol. 30(1), 93–99 (2009)
58. Fernández, F.J., Villaseñor, J., Infantes, D.: Kinetic and stoichiometric modelling of acidogenic fermentation of glucose and fructose. Biomass Bioenerg. 35(9), 3877–3883 (2011)
59. Güngören Madenologu, T., et al.: Kinetic analysis of methane production from anaerobic digestion of water lettuce (Pistia stratiotes L.) with waste sludge. Journal of Chemical Technology & Biotechnology 94(6), 1893–1903 (2019)
60. Bakraoui, M., et al., Kinetics study of methane production from anaerobic digestion of sludge and wastewater recycled pulp and paper. IOP Conference Series: Materials Science and Engineering, 2020. 946: p. 012009
61. Green, D.W., Perry, R.H.: Process Economics, Perry's Chemical Engineers' Handbook, D.W. Green and R.H. Perry, Editors. 2008, McGraw Hill Professional, Access Engineering
62. Jenkins, S.: 2019 CHEMICAL ENGINEERING PLANT COST INDEX ANNUAL AVERAGE. Chemical Engineering 2020 March 20, 2020; Available from: https://www.chemengonline.com/2019-chemical-engineering-plant-cost-index-annual-average/
Figures

Figure 1

Simplified flow sheet of fuel ethanol production from corn via dry grind method.
Figure 2

Simplified flow sheet of different scenarios: combustion of DDGS, (b) combustion of WDGS, (c) anaerobic digestion to produce heat, and (d) anaerobic digestion to produce electricity

Figure 3

The main cash flows for different scenarios with the positive values as the cash flow in and the negative as the cash flow out

Figure 4

Parameter sensitivity analysis to the OPEX of all simulated scenarios with (a) the price of electricity, (b) the price of natural gas and (c) the price of DDGS/WDGS.
11.2

Figure 5

Effect of natural gas price to annual cash flow.

Supplementary Files

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