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Research article

Design of a pre-treatment integrated anaerobic digestion treatment facility for decarbonising whiskey industry: A circular economy perspective

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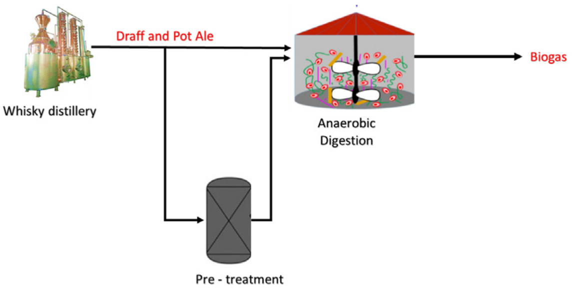
HIGHLIGHTS

- Whiskey distillery by-products, draff and pot ale, was treated by anaerobic digestion.
- The use of feedstock pre-treatment led to 20% increase in methane yield.
- A payback time was reduced from 15.13 to 9.6 years with the integrated pre-treatment.
- The capital cost associated with the proposed facility estimated as €3.6 million.
- The proposed design could reduce carbon footprint of whiskey distillery by 33%.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper outlines the sustainable management of the whiskey distillery by-products, known as draff and pot ale, through anaerobic digestion (AD). The substrates were pre-treated using 0.6M NaOH and high shear homogenizer for 24 h. Substrate pre-treatment helped improve the digestability of lignocellulosic materials towards AD. In addition, the complex cellulose, hemicellulose and lignin contents are disintegrated. A continuous stirred tank reactor with a volume of 1766 m^3 and organic loading rate of 4.04 kg COD/m^3/day operating under mesophilic conditions for 30 days was designed to facilitate the complete digestion of the substrates. Compared with the conventional digesters, the proposed novel pre-treatment method achieved a 20% increase in methane yield. The energy recovery potential using a combined heat and power unit can cover 24 and 42.5% of the thermal and electrical demand of the distillery, respectively. The capital cost of the proposed facility was estimated as €3.6 million with a payback period of 9.60 years. In comparison, there is a payback period of 15.13 years without the pre-treatment. Additionally, this model decreases the distillery's carbon footprint by 33%. Although the proposed design applies to the distillery in Ireland, results could be used to design distillery plants in other countries.

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1. Introduction

In the late 1990s, international policies were proposed to minimize environmental pollution, elevating greenhouse gas (GHG) emissions and global warming (New et al., 2011). Global GHG emissions have continued to rise in recent years due to the increasing world population, industrialization and urbanization, and human activities. The elevating GHG emissions have led to further international efforts to limit the damage, including the European Union (EU) announcing ambitions to achieve a net-zero GHG emission target by 2050 (Deal, 2019). This 'Green Deal' imposes compliance obligations on member states like Ireland. The current trajectory shows that Ireland will be in excess of its cumulative emissions by 25% of the EU 2030 target (Ireland Govt, 2019). This is because Ireland depended on imports to sustain about 67% of its energy requirements. These imports, which consisted of 87% of fossil fuel resources, totalled €4.35 billion (Chiodi et al., 2013; Rogan et al., 2014).

The EU Commission also stressed the essential role of renewable energy resources in reaching the GHG emissions mitigating targets. For instance, the EU Renewable Energy Directive (REDII) has ambitious targets for 2030. The directive aims to reduce GHG emissions by 40% and replace 27% of the energy consumption with renewables (Kang et al., 2020). Long-term plans for a more decarbonized energy system are predicted beyond 2030. Several countries have proposed and implemented radical changes to their energy system to achieve this target, including their heat and electricity distribution. More importantly, the decarbonization of several industries such as cement, metallurgical, whisky and food production industries are essential towards achieving the GHG emissions target.

The whiskey production industry presents a significant economic resource worldwide (Eriksson et al., 2016). Whiskey is also a cultural asset and is often perceived as part of cultural heritage in some countries such as Ireland and Scotland. The Scotch whisky industry accounts for 25% of UK food and drinks exports (Barrena et al., 2018). In Ireland, whiskey production has increased by almost 131% by volume in the last decade, making it the fastest-growing spirit (Kang et al., 2020). Although promising from an economic perspective, the whiskey production industry generates about 7 million tonnes of by-products each year, including pot ale, draff and spent lees (Kang et al., 2020). Therefore, the by-products must be valorized to optimize their economic and environmental benefits to the distillery. During whisky production, the solid residues left behind after mashing are referred to as draff. The liquid residues remaining in the wash and spirit stills after distillation are referred to as the pot ale (Mohana et al., 2009). Every litre of whisky produced between 2.5 – 3.0 kg of wet draff and 8–15 L of pot ale are generated (Mohana et al., 2009), leading to a massive annual waste discharge (Eriksson et al., 2016).

Draff and pot ale production present significant environmental challenges if not properly managed. Pot ale is a dark, caramelized, and bulky organic turbid fluid with high COD (47 g/L) and BOD. (25 g/L) values and a high organic solid content (Graham et al., 2012). Traditionally, pot ale needs to be treated to remove any toxic levels of copper from the pot stills before being released into a large body of water. Before disposal in water bodies, the purification and treatment of pot ale are vital to remove the high COD, BOD, total nitrogen and phosphate levels. This could help prevent the eutrophication of recipient water channels (Kumar et al., 2016). Such treatments include biological, coagulation and flocculation, adsorption or oxidation methods (Mohana et al., 2009). These methods may be economically impractical with no cost-benefit.

In some cases, pot ale has been further concentrated and mixed with draff to form a cattle feed with a moisture content of 10% (Graham et al., 2012). However, some studies have found that the copper remaining in pot ale may be toxic to some animals (Tokuda et al., 1999). Draff is commonly used as cattle feed. However, the economic efficiency of draff utilization is mainly dependent on the cattle feed market (Tokuda et al., 1999). Moreover, drying the draff (and pot ale in some cases) requires about 35% of the plants' thermal energy (Murphy and Power, 2008).

There has been a significant interest in developing alternative ways to valorize by-products from the whisky production industries in recent years. Kang et al. (2020) compared the performance of anaerobic digestion (AD) and dark fermentation as biological treatment routes for the whiskey distillery by-products. Mohana et al. (2009) reviewed different treatment technologies for whisky distillery by-products (Mohana et al., 2009). Eriksson et al. (2016) performed a detailed life-cycle assessment (LCA) of Swedish single malt whisky production. Recently, O'Shea et al.(2021) used the compromise programming approach to explain the advantages and limitations of the AD of the distillery by-products (O'Shea et al., 2021). To the best of the authors' knowledge, the impacts of pre-treatment on AD of pot ale and draff mixture for biomethane production and the subsequent application of the produced biogas in powering the distillery has received scant attention to date.

The present study assesses the feasibility of introducing an effective AD waste treatment facility to co-digest draff and pot ale to produce methane and provide energy to power a large-scale distillery. The proposed technology could foster the decarbonization of the distillery industry. The challenges associated with AD of whiskey waste streams, including their tendency to resist degradation, are tackled in a novel system consisting of pre-treatment methods, neutralization of the feedstock and subsequent AD treatment not yet employed at a large scale. The potential performance and economic feasibility of this model are also assessed.

2. Anaerobic digestion for the valorization of whisky distillery by-products

AD process is a well-known biological conversion process used to convert organic waste into biogas (Adekunle and Okolie, 2015). AD is a complex process performed by a community of microorganisms in four main steps, as displayed in Figure 1.

The breakdown of the feedstock is led by bacteria, with the production of methane mainly carried out by archaea. It is essential to limit the effect of H_2S produced by sulphate-reducing bacteria, which may inhibit both the AD process yield and the reactor itself and pipes due to its toxic and corrosive properties. In addition, the AD process should also be designed so that the methane production by methanogenic archaea is maximized (Jung et al., 2019). The hydrolysis stage can be the rate-limiting step for lignocellulosic materials such as draff and pot ale due to the presence of recalcitrant lignin as well as hemicellulose and degradable amorph cellulose. CO_2 is also a major component of the biogas produced from AD, and its production should be minimized. The methane produced must be upgraded into biomethane by removing the CO_2 and H_2S (Adekunle and Okolie, 2015). Digestate obtained from the AD process could be used as biofertilizer due to its mineral-rich nature or dried and used as feedstock for pyrolysis reaction to produce biochar (Neumann et al., 2016). Details of the factors affecting AD performance and the process mechanism and thermodynamics are outside this study's scope. Readers are referred to excellent studies by Gunes et al. (2019).

AD is widespread in many other sectors, such as urban wastewater treatment plants. However, it is not commonplace in whiskey distilleries in Ireland. Slane Distillery is the sole Irish Whiskey producing plant that has AD capabilities. The plant uses AD to convert pot ale into biogas, followed by biological nutrient removal processes before sending the wastewater to the River Boyne (WEW Engineering, 2019). Many Scottish whiskey plants have been using draff and pot ale for their AD plants. The Glendullan distillery opened an AD plant in 2015 and generated 6000 MW h of thermal energy, reducing fossil fuel demands by 25% within a

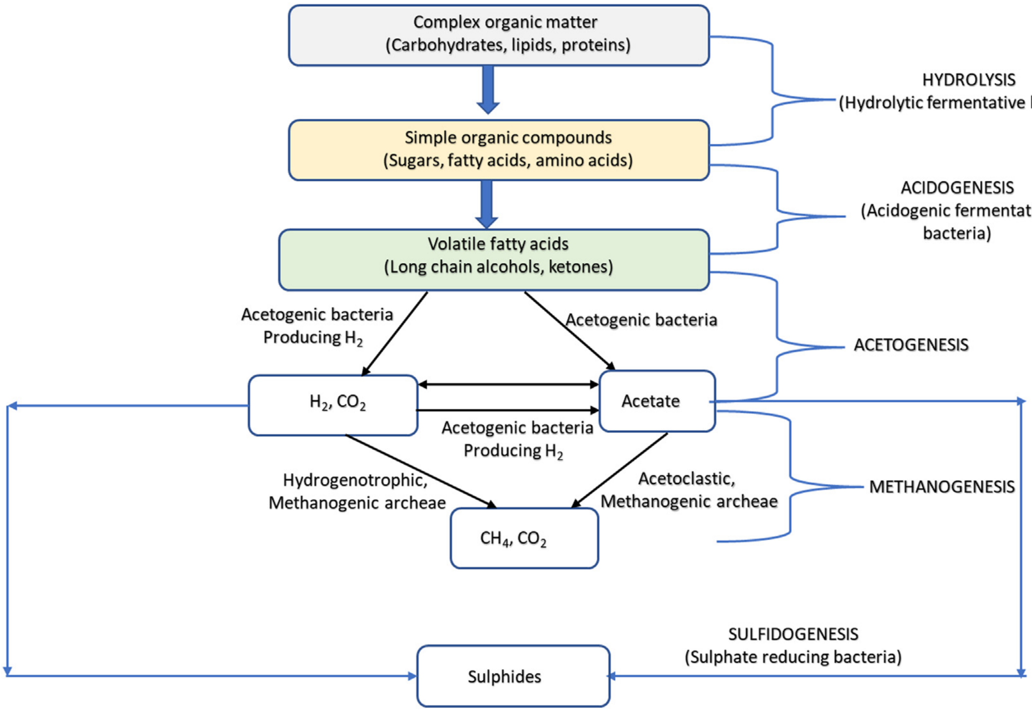

Figure 1. Metabolism of anaerobic digestion process showing the four main stages and the harmful sulphidogenesis side reaction along with the microorganisms involved in each stage (Gunes et al., 2019) with a permission from Elseiver.

single year of opening (Schrieberg, 2017). Hence, there is a prominent niche in the Irish Whiskey distillery scene to implement and improve such successful AD plants.

2.1. AD for the valorissation of whisky distillery by-products

AD offers the benefit of treating the environmentally hazardous waste produced from a whiskey distillery and valorising it in terms of energy that can power the distillery itself, thereby promoting a circular economy. The energy produced could also be sold by entering the national gas grid. Figure 2 shows the properties of distillery effluents before and after AD treatment (Mohana et al., 2009).

As shown in the figure, the AD of distillery effluents led to a decline in the pH, COD, BOD, total volatile solids, total dissolved solids, chlorides, sulphate, and total nitrogen contents of the effluents. Only the total suspended solids showed an increased after AD and it was attributed to the break down of larger solids particles present in the feedstock into smaller/suspendable solids during digestion. The challenge associated with AD of whiskey waste is the recalcitrant properties. Pot ale is very difficult to degrade due to the presence of complex carbohydrates known

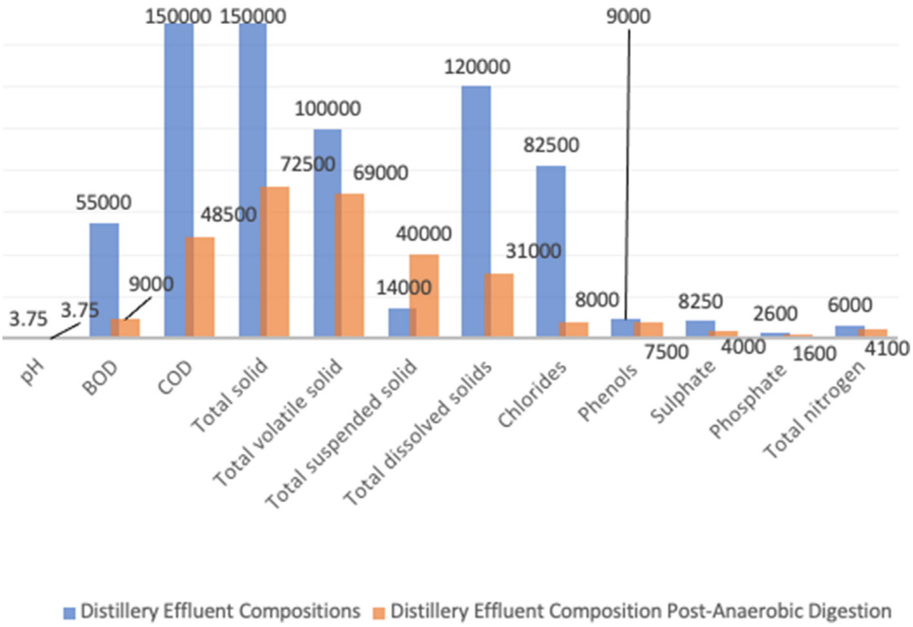

Figure 2. Characteristics of distillery effluent before and after anaerobic treatment adapted from (Mohana et al., 2009) with the average of the value ranges taken to create an average comparison column graph. All values, excluding pH, have units of mg/L.

as dextrins, alongside spent yeast and coagulated protein (Tokuda et al., 1999). Melanoidins are also formed in the pot ale, resulting in the liquid's brown pigment, being difficult to degrade and toxic to microorganisms (Isik et al., 2019). The spent yeast cells also present a degradation barrier with thick cell walls formed by a complex matrix of phosphomannans, chitins, glucans and protein (Mallick et al., 2009).

The draff possibly poses a more difficult feedstock for AD due to its highly lignocellulosic cell walls consisting mainly of cellulose and hemicellulose, cemented together by lignin which is renowned for its aversion to biodegradation (Okolie et al., 2020). Draff consists of 40–55% carbohydrates and up to 30% proteins, making it an ideal energy source for AD with biogas production as long as the microorganisms can access the smaller sugar molecules and amino acids (Kang et al., 2020). Hence, there is emerging research in the process of pre-treatment of lignocellulosic materials to free these smaller, fermentable molecules and enhance biogas production from AD.

The use of alkali reagents that break the links between monomers of dextrins and lignin or between lignin and other polysaccharides has shown to be one of the most promising pre-treatment methods for lignocellulosic materials (Mao et al., 2015). Alkali pre-treatment makes the lignocellulosic biomass more degradable to microbes by increasing the porosity, internal surface area along with structural swelling and disruption of lignin structure (Zheng et al., 2014). Small-scale studies have shown that using NaOH of relatively low concentrations for 1–1.5 h treatment times can improve methane yield compared to untreated pot ale (Gunes et al., 2021). Although acid treatments have also been more effective than alkali, the high costs of acid and the need to neutralise the feed before AD make it unattractive. On the other hand, the addition of alkali agents such as NaOH can aid in overcoming the sharp pH drop resulting from accumulating VFAs from intense acidogenesis when it comes to the AD process (Gunes et al., 2019). It should be mentioned that the downside of alkali or acid pre-treatment is the need to neutralize the pH of the feedstock before entering the AD process to prevent any pH shock to the microbial population.

Mechanical pre-treatment technologies could also be applied to improve the digestibility of lignocellulosic materials (Che Kamarludin et al., 2014). High Shear Homogeniser (HSHs) increase substrates' surface area to enable a higher quantity of interactions between anaerobic bacteria and the substrate (Sežun et al., 2011). Ultrasonic treatment disrupts biological complexes and has been shown to increase the methane yield by 60% and reduce H_2S production from the AD of pot ale. Computer simulations predict maximum methane yield using a combination of NaOH and ultrasonic (Gunes et al., 2019). The combination of both mechanical (ultrasonic at 40% amplitude ratio) and alkali (NaOH up to 0.6M) has been shown to have the potential in enhancing methane production from the AD of pot ale while limiting H_2S production (Gunes et al., 2021).

3. Integrated anaerobic digestion plant design

The distillery was designed to produce approximately 2 million litres of whiskey per annum, based on the studies of (Kang et al., 2020). The amount of waste produced, including pot ale and draff in a typical large-scale distillery, is summarized in Table 1.

The co-digestion of pot ale and draff is assumed to be carried out at a hydraulic retention time (HRT) of 30 days. Furthermore, the AD facility required organic loading rate (OLR) is set at 4.04 kg COD/m^3/d. Detailed calculations of OLR are given in Supplementary Data (S.1: Calculation of Organic Loading Rate). The addition of distillery spent washes can be considered if inhibitory phenolic compound concentrations prove too high. However, the proposed design will consider only draff and pot ale AD. The high HRT will result in large reactor volumes; however, it is required to ensure complete digestion of the pot ale-draff mix.

Table 1. Quantities of pot ale and draff discharged in a typical large-scale with two million L whiskey production capactity per year.

Whiskey produced per year	2,000,000L	
Waste type	**Pot ale (L)**	**Draff (kg)**
Waste discharged per litre of whiskey production	8	2.75
Waste discharged per year (365.25 days)	16,000,000	5,500,000
Waste produced per day	43,805.6	15,058.2

Considering the simplicity of design and lower configurations costs associated with single-stage mesophilic AD operations, this project aims to implement an individual digester operating at a mesophilic temperature range (35–37 °C). Mesophilic temperature enables stable operation at relatively low energy requirements. Additionally, a set-point pH of 7.1 was targeted for additional stability. The pH was set as the mid-point between optimal methanogenesis pH of 6.7–7.5 and will help to maintain stable operation. The temperature and pH were be controlled using a jacket and acid/base drip connected to meters within the digester.

3.1. Pre-treatment and neutralisation vessel design

Implementing a large-scale pot ale and draff pre-treatment process before AD is one of the main objectives of the proposed design. Due to the incompatibility of ultrasonic devices at a large scale, HSH technology coupled with highly effective alkali (NaOH) treatment was the preferred pre-treatment technology. Sežun et al. (2011) used HSH for the treatment of draff, recording 11.3% degradation in lignin content before AD. While lignin degradation was not significant, the use of such HSHs can fragment draff substrate below a mean particle size of 0.5mm, allowing for more excellent substrate surface microbial interactions.

The HSH device can be configured as vertical mixers with a motor above the PT vessel. The high-speed rotor and stator within the head of the HSH create suction potential from the bottom of the vessel that is driven to the centre of the head. The rotor then mechanically shears the substrate at up to 20 m/s, while the stator hydraulically shears it as it leaves through the slots in the head of the HSH at high speed. This generates a strong circulation flow inside the vessel. More importantly, it creates a homogenous mixture of pot ale and draff, which is essential for successful AD and creating an even environment with little dead spots in the digester.

A pre-treatment duration of 24 h was chosen to degrade and homogenise the substrates effectively. This is also manageable for producing daily feedstock in a continuous AD operation in a large-scale industry. The next step is to spatially design a pre-treatment vessel that combines NaOH and HSH pre-treatment methods for the AD of distillery waste materials. Assuming 1kg of draff occupies a volumetric equivalent of 1L of pot ale, the process must treat up to 58,863.60 L of waste each day. The pre-treatment process would have to be operated in batch mode to ensure all waste undergoes the same treatment to create a homogenous feedstock for AD. Therefore, the pre-treatment vessel volume can be taken to be 60,000 L or 60m^3. The dimensions of a stainless-steel vessel for PT can assume the typical geometrical ratios of a microbial bioreactor (CSTR design) and be of cylindrical shape. Details of the pre-treatment vessel dimensions and the calculations are presented in Supplementary Data (S.2: Calculation of Vessel Dimensions). The vessel requires a diameter of 4.24m to treat waste built up over a day. Using these geometric ratios, the height of the contents would therefore be 4.24m. However, 75% of designed reactor volumes are typically used as the working (i.e., contents) volume, with the remaining 25% of the reactor used for gas space. In this case, the extra height is helpful to account for the vortex formed by the HSH. Hence, the actual height of the reactor would need to be 5.66m. Figure 3 depicts the primary measurements of the pre-treatment vessels.

Due to the high pH created by alkaline pre-treatment, the contents need to be neutralized prior to AD. Therefore, another neutralization vessel is required after the pre-treatment vessel, simultaneously acting as a holding vessel for the continuous feed to the digester. The vessel will neutralize the feedstock to a pH of 8.0. This is in the same pH range

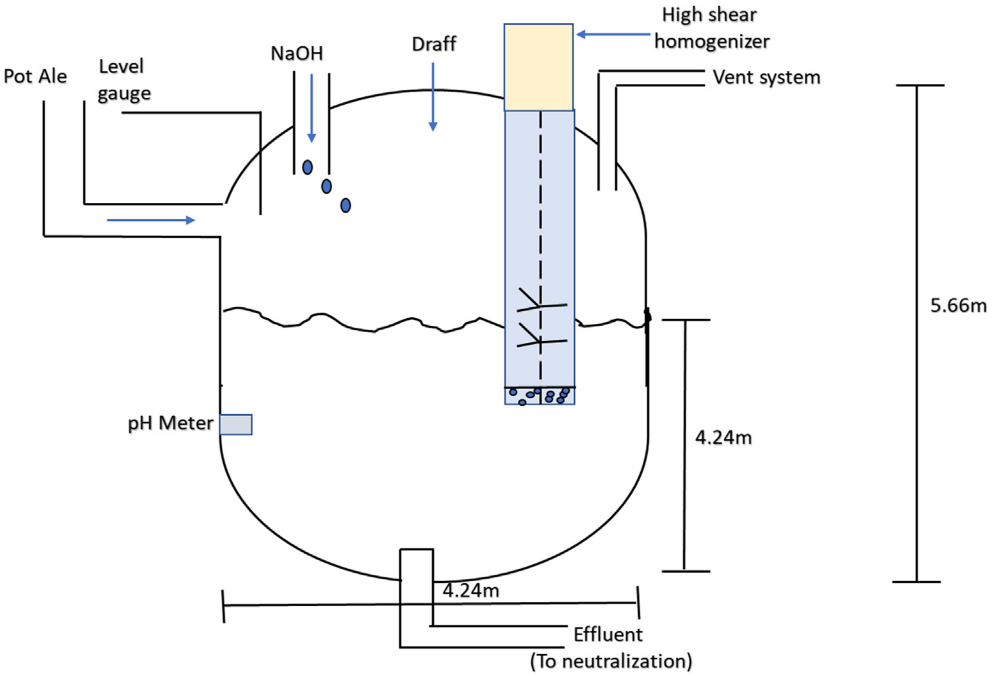

Figure 3. An overview of the pre-treatment vessel with dimensions, PT methods and controls and influent/effluent flows depicted.

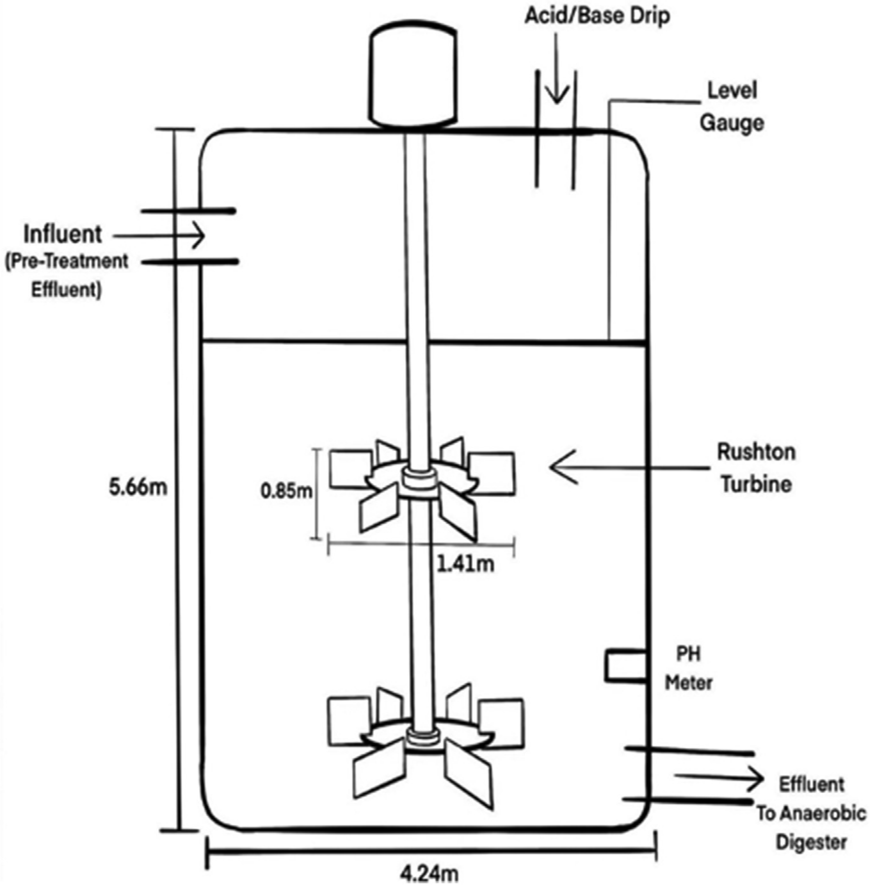

Figure 4. An overview of the proposed neutralization vessels.

(8.0–8.5) as usual seed inoculums from wastewater-activated sludges or other sources (Kumar et al., 2016). Adding feedstock with a pH of 8.0 will prevent damage to AD microorganisms while it also combats the pH drop caused by acidogenesis. Therefore, the use of a neutralizer is cost-effective in controlling the feedstock pH.

The neutralization vessel can be a simplified configuration as a simple stirred tank with an acidic drip and pH meter at the outlet of the feedstock entering the digester. Hence, the same dimensions of the PT vessel can be employed for the neutralization vessel. This vessel is receiving the pre-treated effluent. Again, a feedback system from a pH meter is used for acid addition to reach a pH of 8. Rushton turbines are used to maintain homogenization and prevent settling of the mixed feedstock. Once this vessel receives a days' worth of pre-treated waste, it neutralizes it and begins to release the feedstock to the digester gradually at a rate according to the OLR and HRT. An overview of the neutralizer is presented in Figure 4.

3.2. Anaerobic digester design

The AD reactor is where the main conversion of distillery waste into biogas occurs. The reactor is designed as a continuous stirred tank reactor (CSTR). The dimensions of the reactors are determined by the expressions in Supplementary Data (S.2: Calculation of Vessel Dimensions). The diameter of the AD reactor works out to be 13.10m, with a height of 17.47m. The impellor dimensions are 4.37m in diameter and 2.62m wide. The thickness of the reactor jacket works out as 1.31m. As mentioned previously, the surplus volume in these calculations is mainly used as gas space. However, this volume may also account for inoculum-substrate ratios in the process. In the digester, the microbial population digests the draff-pot ale mix after start-up. This produces methane and other gases, which are collected using a biogas collector at the top of the vessel, which is then further purified to produce biomethane that can be used to generate energy. The process parameters are monitored by in-line pH meters. At different heights in the reactor, offline sampling ports test for nutrient levels, toxic compound accumulation, and microbial health. Rushton turbines ensure a mixture of the environment to prevent dead spots and settling. A mechanical foam breaker is used to avoid the build-up of excess foam produced from microbial activities. The pre-treated feedstock enters at the top of the vessel coming from the neutralization vessel and leaves as digestate at the same rate from the bottom of the reactor. This is opposed to using an effluent overflow. This prevents the uneven rise of the liquid pot ale fraction compared to the denser draff fraction, resulting in the accumulation of digested draff at the bottom of the digester to create an unwanted draff to pot ale ratio. Figure 5 provides an overview of the CSTR anaerobic digester. An overall summary of each vessel configuration and dimension is presented in Table 2.

4. AD plant production capacity, capital cost and energy recovery

The proposed AD facility for draff and pot ale treatment is in line with common large-scale volumes, as shown in Table 3. In a distillery such as Roseisle, with 5–6 times the production capacity of the model distillery used in this project, it has 4–5 times the capital cost of the proposed AD plant. The pre-treatment vessel may need further investigation regarding the volumes and cost associated with NaOH addition and the cost of acid used in neutralization. The homogenizer size may need to be ordered as a personalized size from a company such as INOXPA, which may incur additional costs. The capital costs of these smaller vessels are calculated as high-end stainless-steel reactors with agitator and jacket features for

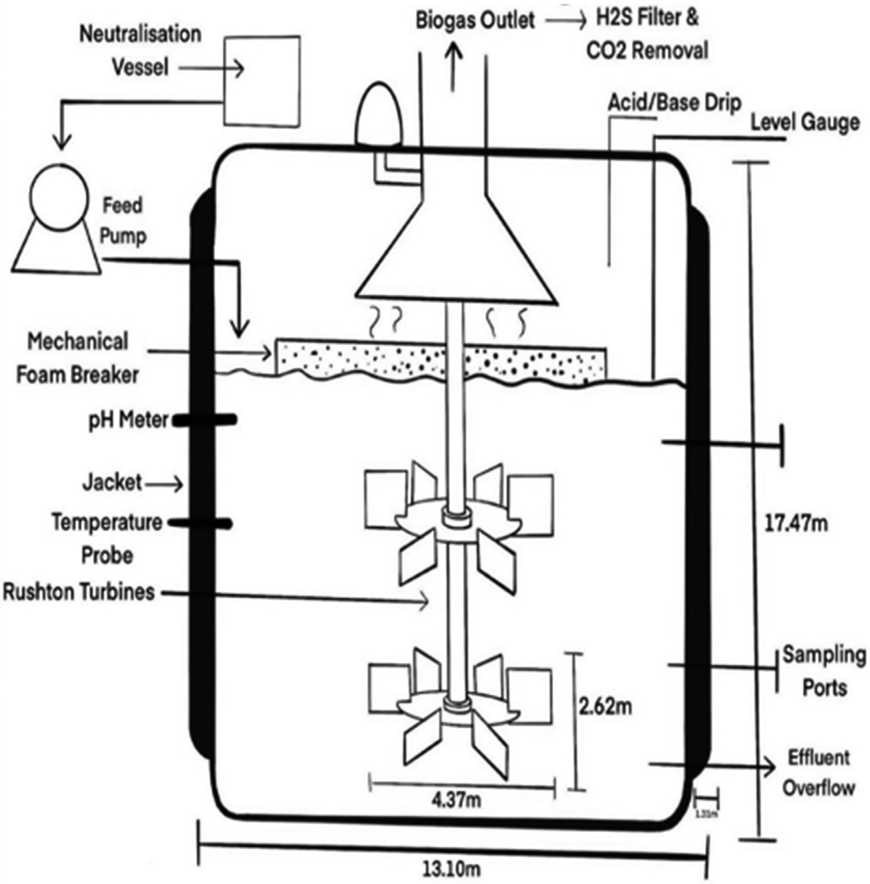

Figure 5. An overview of the proposed CSTR Anaerobic digester.

Table 2. Summary of each vessel configurations and dimensions.

Vessel	Design	Working Volume (m^3)	Actual volume (m^3)	Diameter (m)	Height (m)	Impellor	Jacket
Pre-treatment	CSTR	60	79.92	4.24	5.66	HSH	None
Neutralisation	CSTR	60	79.92	4.24	5.66	Rushton 1.41m d_i 0.85m w_i	None
Anaerobic Digester	CSTR	1766	2354.6	13.10	17.47	Rushton 4.37m d_i 2.62m w_i	Jacket 1.31m thick

See Supplementary Data (S.2: Calculation of Vessel Dimensions) for details.

Table 3. Comparison of the production capacity, capital cost and energy production of AD plants.

Distillery	Yearly whiskey production (M^3)	AD plant	Feedstock	Energy produced per year	Energy demand recovered	Capital cost (£)	References
Dailuaine (Diageo)	3,300	AD and CHP.	Liquid residue	0.5 MW	40%	6,000,000	(Media GmbH & Co. KG, 2018; Organics et al., 2014; Scottish Whisky Association, 2009))
Roseisle	10,000–12,000	AD and CHP	Pot ale	8.6 MW	84%	17,000,000	(Andrews et al., 2011; Wood, 2015)
Cameronbridge	120,000	AD and CHP (Membrane filtration for water recovery)	-	30 MW	95%	65,000,000	(Andrews et al., 2011; Difford, 2019; Duguid and Strachan, 2016)
Glendullan	-(Treats 1,000m^3 waste per day)	AD and boiler	Draff and pot ale	365 MW	25% fossil fuel reduction	-	(Beverage 2016; Gueterbock and Sangosanya, 2017)
North british distillery	60,000	AD and CHP	Liquid residues	7.2 MW	-	-	(Brinkerhoff, 2012; Duguid and Strachan, 2016)
Girvan (william grant & sons)	-	AD and CHP		21.9 GW_eh and 5.5 $GW_{th}h$	261% electricity and 10% thermal	-	(Duguid and Strachan, 2016; Hamill, 2015; Scotch Whisky Association, 2009)
Research project	2,000	AD and CHP.	Draff and pot ale	3.15 GW_eh and 4.05 $GW_{th}h$	425% electricity and 24% thermal	3,600,000	-

See Supplementary Data (S.3: Calculation of Energy Recovery from AD and the Related Savings) for detailed calculations.

simplicity. Moreover, details of the energy recovery calculations and related savings are presented in Supplementary Data (S.3: Calculation of Energy Recovery from AD and the Related Savings).

The energy consumption in whiskey distilleries can be split into two categories – electricity (e) and thermal (th) requirements. On average, the energy requirements per litre of whiskey produced equates to 0.37 kWeh and 8.46 kWth (Meadows, 2015). Therefore, a whiskey distillery producing 2 million litres per annum requires 0.74 GWeh and 16.92 GWth. The energy potential of biomethane is 10 kWh/m^3 (Kang et al., 2020). The biogas produced from untreated pot ale and draff has been estimated at 550 L/kg COD removed and 648 L/kg VS removed, respectively. The methane portion of biogas produced from pot ale is approximately 73%, with draff at 60% methane of the resulting biogas (Duguid and Strachan, 2016). The potential for methane production in the following calculations assumes that the anaerobic microbes completely digested 100% of the COD of pot ale and VS content of draff.

AD of whiskey distillery waste streams has shown an 87% reduction in COD (Gunes et al., 2019, 2021). Pre-treatment methods have been shown to increase methane yields with varying yield improvements depending on the pre-treatment method as follows: 16% (acid), 60% (ultrasonic) and 115% (alkali) (Gunes et al., 2019, 2021). On the other hand, no studies have measured yield improvements using the combination of several pre-treatment methods. There have also been little methane improvements observed by using pre-treatment when digesting draff alone, with most changes seen in structural composition, thereby making fermentable sugars more accessible (Sežun et al., 2011). Therefore, in deciding a methane yield improvement due to pre-treatment integration, a conservative increase of 20% (both draff and pot ale) has been assumed. Further research is needed in this field at a large scale to determine whether pre-treatment technologies can indeed increase methane yields above 20%.

Table 4 depicts the methane production and energy potential associated with using an AD facility utilizing pot ale and draff as a feedstock. By using AD with pre-treatment, a potential 4.05 GWth and 3.15 GWeh can be produced per year with draff and pot ale whiskey wastes. This would cover 24% of the plant's thermal energy requirements and provide 42.5% of the plant's electricity requirements for the year.

Results from Table 4 indicate that there is income potential from the above energy generated through AD. The cost savings can arise from the replacement of natural gas and electricity usage through methane produced on-site, which have respective costs of €0.0427/kWthh and €0.1518/kWeh (SEA1a, 2018). Therefore, a savings of €323,700 can be achieved from reductions in thermal energy requirements through the installation of the AD facility as described above. A further €112,300 can be saved through the reduction of electricity requirements of the distillery.

The excess electricity generated can enter the grid at a sale price of €0.15/kWeh (Kang et al., 2020). Hence, earnings of up to €778,900 can be produced through the sales of excess electricity.

5. Decarbonisation of the whiskey distillery and the related savings

Global warming potential generated from whiskey production is estimated at an equivalent of 2.3 kg CO_2 per litre of whiskey produced (Duguid and Strachan, 2016). Therefore, a whiskey distillery producing 2

Table 4. The potential energy produced per year by an AD plant with integrated PTs based on the COD and VS contents of pot ale and draff assuming complete COD removal.

	POT ALE	Draff	References
Volume per year	16,000,000 L	5,500,000 kg	-
COD Content of POT ALE/VS Content of draff	0.047 kg/L	0.21 kg/kg	(Duguid and Strachan, 2016; Graham et al., 2012)
Potential COD/VS removed per year	752,000 kg	1,155,000 kg	-
Biogas production rate	550 L/kg C.O.D. removed	648 L/kg VS removed	(Duguid and Strachan, 2016; Moletta, 2005)
Potential biogas produced	4.136×10^8 L	7.4844×10^8 L	
Methane content	73%	60%	(Duguid and Strachan, 2016; Moletta, 2005)
Methane produced	301,928 m^3	449,064 m^3	-
Pre-treatment improvement	20% (× 1.2)	20% (× 1.2)	-
Improved methane yield	362,313.6 m^3	538,867.8 m^3	-
Energy potential of methane	10 kWh/m^3	10 kWh/m^3	(Kang et al., 2020)
Energy potential per year	3.62 GWh	5.39 GWh	-
Total energy potential	9.01 GWh		-
Thermal energy efficiency	45%		-
Thermal energy recovery	**4.0545 $GW_{th}h$**		-
Electrical energy efficiency	35%		-
Electrical energy efficiency	**3.1535 $GW_{e}h$**		-

million litres per annum will release an equivalent of 4600 tonnes of CO_2 into the atmosphere. If a distillery became utterly self-sufficient in energy requirements through the application of AD of its waste streams, it has the potential to be carbon neutral. Even though the combustion of the biogas produced releases CO_2, and the microbes produce a small amount of CO_2 that is removed from the biomethane, this can be effectively negated due to the fact that the growth of the crops that power the process will consume an equivalent amount of CO_2 (Kang et al., 2020). In Ireland, 0.437 kg of CO_2 equivalent is released per kWeh used, while 0.205 kg is produced per kWthh (Seal1b, 2018). Therefore, the distillery in question produces approximately 323 tonnes of CO_2 from electrical use and another 3,469 tonnes for thermal usage. Hence, using the potential energy produced by the AD plant as discussed above, all CO_2 emissions produced by electricity usage could be removed.

About 45% of the emissions caused by thermal energy usage can be removed in the system in question, equating to a reduction in 1560 tonnes of CO_2. Since May 2014, Ireland's carbon tax was increased to €20 per tonne of CO_2 emitted (Citizensinformation.ie, 2020). Therefore, there is a potential €37,600 in CO_2 tax reductions available to the distillery with the installation of this AD facility.

6. Economic viability of pre-treatment integrated AD process

The operating cost of an AD plant without pre-treatment is €5 per tonne of treated waste, which equates to 4.55% of the capital cost (Browne et al., 2011). Assuming that this capital cost rate holds for the additional pre-treatment operating costs, the operating cost for a pre-treatment integrated AD facility for a year is about €165,500. The transport of the significant volumes of digestate produced is a major cost of the system every year. The cost is highly dependent on the distance the digestate must be transported, with distances of 20 km approximately costing €10 per m^3 of digestate (Aponte Garcia, 2016). This would equate to (21,500 m^3/y) €215,000 per year. This does not consider possible decreases in volume resulting from pre-treatment and AD processes. The final major cost per year is the loss on cattle feed sales, which are usually at €100/tonne (dried) (Kang et al., 2020). It is assumed that pot ale mass (after evaporation) is negligible. For ease of calculation, it is assumed 50% mass of wet draff is water, and this is removed once drying is completed. Therefore, 2,750 tonnes of cattle feed are worth €275,000, which is lost by the distillery to the AD facility.

As per other wastewater AD processes, the digestate possesses the possibility to be valorized as a fertilizer (Surendra et al., 2014). Digestate is a co-product of AD. It contains both undigested feedstocks and microbial biomass, which can be high in nitrogen, phosphorous and potassium, which is ideal for organic fertilizer (Aboderheeba and Eng, 2013). However, the disposal of raw distillery waste streams is hazardous to vegetation by reducing soil alkalinity and inhibiting growth and germination at low concentrations (Kannan and Upreti, 2008). The concentration of copper within pot ale has also been noted to be toxic to certain animals, affecting feasibility as a fertilizer (Tokuda et al., 1999). That said, a Diageo distillery at Dailuaine uses mono-digestion of pot ale to produce methane, with the solid fraction of the digestate used as a fertilizer and the liquid part is discharged to a river in line with regulatory requirements (Gunes et al., 2019). A similar method may be adapted for the digestate of co-digestion of pot ale and draff. Therefore, further investigation into the growth of plants using large-scale digestate from mixed pot ale and draff AD as a fertilizer is required to validate and valorize the digestate from the process. The extra costs associated with digestate storage could be negated by the current cost of the dried draff and pot ale storage. The profits and expenses related to the installation of the AD facility are summarised in Table 5.

The cost related to planning permissions, land costs, contractor fees, wages and other regulatory issues are not included. It also assumes operational cost does not consider the costs associated with start-up and microbial culture development. This means it is a simplified version with marginally advanced payback times. However, the difference between implementing a pre-treatment process and not doing so is clearly observed, with payback periods of 9.60 years and 15.13 years, respectively. The net profit for the AD facility with pre-treatment is €379,000 per year.

It is clear that the proposed AD facility has the potential to be both economically feasible and environmentally advantageous. While pre-treatment methods have been shown to lead to almost complete digestion in small-scale studies, the above economic analysis can be improved by testing actual digestion rates within the digester once it is operational. For example, with a digestion rate of 80% (VS and COD), the net profit per year is approximately €172,000 in the pre-treatment scenario with a payback period of 21 years. While 80% is an under-achieving digestion rate, this shows that the AD facility may be economically feasible for a large-scale distillery without optimal performance and will begin to profit after 20 years.

Furthermore, it has been shown that monitoring the accumulation of toxic compounds that arise from degraded lignin is essential within the co-digestion of draff and pot ale. The use of spent wash with low organic solid content can be considered in order to dilute such compounds below the toxic threshold and increase moisture content within the digester. The volume addition of this added waste would have to be considered in terms of digester dimensions. There is also the possibility to solely digest pot ale and retain the sales of cattle feed, particularly in areas where the dried draff is a relied upon feedstock for farms. This would significantly decrease methane yields and thus profits while also reducing the capital cost of the AD plant. The use of both pot ale and draff saves the storage of the cattle feed. However, these same stores would likely be needed for the use of the digestate as a biofertilizer. Beyond this, the AD facility itself will provide jobs in both urban and rural areas, depending on the distillery location. However, land prices will also vary based on location. It is evident that large-scale implementation of pre-treatment processes

Table 5. Theoretical cost-benefit analysis of the set-up of an AD waste treatment facility for whiskey distilleries, highlighting the financial advantage of employing PT technologies.

Details	Non-Pre-treated AD (€)	Pre-treated AD (€)
Costs		
Pre-treatment vessel	-	303,087
Neutralisation/Holding vessel	303,087	303,087
Anaerobic Digester [**Calculation 4**]	2,490,310	2,490,310
CHP Plant (connected to grid)	540,599	540,599
Capital Cost	**3,333,996**	**3,637,083**
Operating cost per year	151,697	165,487
Digestate transport/processing (20km)	215,000	215,000
Cattle feed loss	275,000	275,000
Operating Cost Per Year	**641,697**	**655,487**
Profits per year		
Savings on natural gas (@ €42.7/$MW_{th}h$) (from heat produced and no draff drying/pot ale evaporation)	354,998	425,997
Savings on electricity (@ €151.8/MW_eh) (from electricity use on site and sales of extra electricity)	487,798	585,357
Reduction of CO_2 emissions on site (@ €20/ton)	19,264	23,117
Total Income per Year	**862,060**	**1,034,471**
Net Income per Year	220,363	378,984
Payback time (Years)	**15.13**	**9.60**

See Supplementary Data (S.3: Calculation of Energy Recovery from AD and the Related Savings, S.4: Calculation of Decarbonisation of the Whiskey distillery and the Related Savings and S.5: Calculation of Capital Costs of AD Facility) for details.

before co-digestion of pot ale and draff requires further investigation. Small-scale studies are promising for increasing methane yields from alkali and mechanical pre-treatment. The large-scale application has been shown here to increase economic feasibility alongside decreasing the carbon footprint of a whiskey distillery. Due to the excess electricity generated from the AD plant and only 24% of thermal demands covered, the optimization and improvement of thermal energy production may improve the model shown and should be investigated further.

7. Conclusions

The present study assesses the feasibility of introducing an effective AD waste treatment facility to co-digest draff and pot ale to produce methane and provide energy to aid in powering a large-scale distillery, and help in decarbonizing the distillery process. The installation of an AD plant in a whiskey distillery that produces 2,000,000 L of wastewaters per year has been shown to be both economically feasible and environmentally beneficial. The co-digestion of pot ale and draff whiskey by-products in a distillery of this size has the potential to produce up to 750,000 m^3 of methane per year. This volume of methane converted to energy in a CHP unit can completely cover the distillery's electricity demands while covering 24% of the thermal energy requirements of the plant. With the connection of the CHP to the natural gas grid in Ireland, the excess 325% of electrical energy produced can provide further profits and decrease CO_2 emissions elsewhere. The inclusion of wet draff as a substrate removes the need for drying to convert it to cattle feed, saving a further 35% of the distillery's thermal energy demand while incurring losses of feed sales. The application of combined alkali and high shear homogenization pre-treatment technologies before anaerobic digestion is proposed to overcome the degradation challenges associated with the lignocellulosic feedstock and, therefore, improve methane yields. The proposed anaerobic digestion facility has a pre-treatment vessel capable of containing one day's worth of pot ale and draff and operating for 24 h, which then dispenses to a neutralization vessel that continuously feeds the digester. The digester can treat one month's worth of waste at one time in continuous feed and effluent mode. The capital costs associated with this facility are approximately €3,600,000. Vessel dimensions, costs, and energy production fall within parameters of existing AD plants in the UK and Germany. The payback period of the proposed facility is 9.6 years which is superior when compared to a facility that does not include pre-treatment technologies. Furthermore, the facility decreases the distillery's carbon footprint by over 1,000,000 kg of CO_2 per year, which is a 30% decrease and a subsequent decrease in carbon taxes. This design is considered to be globally replicable considering the whiskey manufacturing process does vary significantly. Correspondingly the characteristics of the by-products are not significantly different based on the distillery location. Future studies will focus on a detailed techno-economic analysis, including discounted cash flow analysis and Monte Carlo simulation sensitivity analysis.

Declarations

Author contribution statement

Cormac Dalton: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Jude A. Okolie: Analyzed and interpreted the data; Wrote the paper, respond to reviewers comment, supervison.

Paul Davis: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data, supervison.

Burcu Gunes: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper, supervison.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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References

Aboderheeba, A.K.M., Eng, M., 2013. A Thesis Submitted for the Degree of Doctor of Philosophy 242.

Adekunle, K.F., Okolie, J.A., 2015. A review of biochemical process of anaerobic digestion. Adv. Biosci. Biotechnol. 6, 205–212.

Andrews, J.M.H., Hancock, J.C., Ludford-Brooks, J., Murfin, I.J., Houldsworth, L., Phillips, M., 2011. 125th anniversary review: some recent engineering advances in brewing and distilling. J. Inst. Brew. 117, 23–32.

Aponte Garcia, G., 2016. The Sustainable City XI - Google Books [WWW Document].

Barrena, R., Traub, J.E., Gil, C.R., Goodwin, J.A.S., Harper, A.J., Willoughby, N.A., Sánchez, A., Aspray, T.J., 2018. Batch anaerobic digestion of deproteinated malt whisky pot ale using different source inocula. Waste Manag. 71, 675–682.

Beverage, F., 2016. Bio-energy plants transform whisky distillery sector. Filtr. Sep. 53, 18–19.

Brinkerhoff, W.P., 2012. Future Energy Opportunities: A Guide for Distillers.

Browne, J., Nizami, A.S., Thamsiriroj, T., Murphy, J.D., 2011. Assessing the cost of biofuel production with increasing penetration of the transport fuel market: a case study of gaseous biomethane in Ireland. Renew. Sustain. Energy Rev. 15, 4537–4547.

Che Kamarludin, S.N., Jainal, M.S., Azizan, A., Safaai, N.S.M., Daud, A.R.M., 2014. Mechanical pre-treatment of lignocellulosic biomass for biofuel production. Appl. Mech. Mater. 625, 838–841.

Chiodi, A., Gargiulo, M., Deane, J.P., Lavigne, D., Rout, U.K., Ó Gallachóir, B.P., 2013. Modelling the impacts of challenging 2020 non-ETS GHG emissions reduction targets on Ireland's energy system. Energy Pol. 62, 1438–1452.

Citizensinformation.ie, 2020. Carbon Tax [WWW Document]. URL (accessed 4.27.21). https://www.citizensinformation.ie/en/money_and_tax/tax/motor_carbon_other_taxes/carbon_tax.html.

Deal, E.G., 2019. European Commission, 2019. The European Green Deal, Brussels 11.12.2019. EUR-Lex [WWW Document]. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640&qid=1615330372954 - Google Search.

Difford, S., 2019. Cameronbridge Grain Distillery [WWW Document]. URL (accessed 5.8.21). https://www.diffordsguide.com/producers/110/cameronbridge-grain-distillery.

Duguid, L., Strachan, P., 2016. Sustainable Energy Using Anaerobic Digestion of By-Products: Islay Whisky Industry Case Study.

Eriksson, O., Jonsson, D., Hillman, K., 2016. Life cycle assessment of Swedish single malt whisky. J. Clean. Prod. 112, 229–237.

Graham, J., Peter, B., Walker, G., 2012. Characterisation of the Pot Ale Profile from a Malt Whisky Distillery.

Gueterbock, M.R., Sangosanya, M.B., 2017. Developing on-site anaerobic digestion for smaller businesses in the food and drink sector. Eng. Amp Technol. Ref. 1.

Gunes, B., Stokes, J., Davis, P., Connolly, C., Lawler, J., 2019. Pre-treatments to enhance biogas yield and quality from anaerobic digestion of whiskey distillery and brewery wastes: a review. Renew. Sustain. Energy Rev. 113, 109281.

Gunes, B., Stokes, J., Davis, P., Connolly, C., Lawler, J., 2021. Modelling and optimisation of the biogas yield after hybrid alkaline-ultrasonic pre-treatment in the early stages of anaerobic digestion of pot ale to shorten the processing time. Process Saf. Environ. Protect. 146, 43–53.

Hamill, A., 2015. Improved Treatment of Distillery Wastes Project Ref: 2013-ET-CP-47 58. National Waste Prevention Programme 2014-2018 Final Report for Green Enterprise Programme (GEP.) Phase 2 Improved Treatment of Distillery Wastes.

Ireland Govt, 2019. Government of Ireland, 2019. "Climate Action Plan 2019 - to Tackle Climate Breakdown". Google Search [WWW Document].

Isik, O., Abdelrahman, A.M., Ozgun, H., Ersahin, M.E., Demir, I., Koyuncu, I., 2019. Comparative evaluation of ultrafiltration and dynamic membranes in an aerobic membrane bioreactor for municipal wastewater treatment. Environ. Sci. Pollut. Res. 26, 32723–32733.

Jung, H., Kim, J., Lee, C., 2019. Temperature effects on methanogenesis and sulfidogenesis during anaerobic digestion of sulfur-rich macroalgal biomass in sequencing batch reactors. Microorganisms 7.

Kang, X., Lin, R., O'Shea, R., Deng, C., Li, L., Sun, Y., Murphy, J.D., 2020. A perspective on decarbonizing whiskey using renewable gaseous biofuel in a circular bioeconomy process. J. Clean. Prod. 255, 120211.

Kannan, A., Upreti, R.K., 2008. Influence of distillery effluent on germination and growth of mung bean (Vigna radiata) seeds. J. Hazard Mater. 153, 609–615.

Kumar, G., Zhen, G., Kobayashi, T., Sivagurunathan, P., Kim, S.H., Xu, K.Q., 2016. Impact of pH control and heat pre-treatment of seed inoculum in dark H2 fermentation: a feasibility report using mixed microalgae biomass as feedstock. Int. J. Hydrogen Energy 41, 4382–4392.

Mallick, P., Akunna, J.C., Walker, G.M., 2009. Anaerobic digestion of distillery spent wash: influence of enzymatic pre-treatment of intact yeast cells. Bioresour. Technol. 101, 1681–1685.

Mao, C., Feng, Y., Wang, X., Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renew. Sustain. Energy Rev. 45, 540–555.

Meadows, S., 2015. Department of Mechanical and Aerospace Engineering Anaerobic Digestion and Resource Use within the Scotch Whisky & UK Beer Industries. Univerisy of Strathclyde.

Media GmbH & Co. KG, 2018. Dailuaine Distillery - Whisky.Com [WWW Document]. URL (accessed 5.8.21). https://www.whisky.com/whisky-database/distilleries/details/dailuaine.html.

Mohana, S., Acharya, B.K., Madamwar, D., 2009. Distillery spent wash: treatment technologies and potential applications. J. Hazard Mater. 163, 12–25.

Moletta, R., 2005. Winery and distillery wastewater treatment by anaerobic digestion. Water Sci. Technol. 51, 137–144.

Murphy, J.D., Power, N.M., 2008. How can we improve the energy balance of ethanol production from wheat? Fuel 87, 1799–1806.

Neumann, J., Meyer, J., Ouadi, M., Apfelbacher, A., Binder, S., Hornung, A., 2016. The conversion of anaerobic digestion waste into biofuels via a novel Thermo-Catalytic Reforming process. Waste Manag. 47, 141–148.

New, M., Liverman, D., Schroder, H., Anderson, K., 2011. Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 369, 9–19.

O'Shea, R., Lin, R., Wall, D.M., Browne, J.D., Murphy, J.D., 2021. Distillery decarbonisation and anaerobic digestion: balancing benefits and drawbacks using a compromise programming approach. Biofuel Res. J. 8, 1417–1432.

Okolie, J.A., Nanda, S., Dalai, A.K., Kozinski, J.A., 2020. Chemistry and specialty industrial applications of lignocellulosic biomass. Waste Biomass Valorization 12, 2145–2169.

Organics, C., New, T., Rock, L., 2014. Anaerobic Digestion. BioCycle, p. 27.

Rogan, F., Cahill, C., Daly, H., Dineen, D., efficiency, J.D., 2014. LEAPs and Bounds—An Energy Demand and Constraint Optimised Model of the Irish Energy System. Springer.

Schrieberg, F., 2017. Putting Whisky Waste to Good Use Scotch Whisky [WWW Document]. Scotch Whisky.

Scotch Whisky Association, 2009. Scotch Whisky Sector Supporting a Low Carbon Economy.

SEA1a, 2018. SEAI, 2018a. Sustainable Energy Authority Ireland; Commercial/Industrial Fuels Comparison of Energy Costs. https://www.seai.ie/publications/Commercial-Fuel-Cost-Comparison.pdf - Google Search [WWW Document].

Seal1b, 2018. SEAI, 2018b. Sustainable Energy Authority Ireland; CO2 Emissions Report [WWW Document]. https://www.seai.ie/data-and-insights/seai-statistics/key-publications/co2-emissions-report/ - Google Search.

Sežun, M., Grilc, V., Zupančič, G.D., Marinšek-Logar, R., 2011. Anaerobic digestion of brewery spent grain in a semi-continuous bioreactor: inhibition by phenolic degradation products. Acta Chim. Slov. 58, 158–166.

Surendra, K.C., Takara, D., Hashimoto, A.G., Khanal, S.K., 2014. Biogas as a sustainable energy source for developing countries: opportunities and challenges. Renew. Sustain. Energy Rev. 31, 846–859.

Tokuda, M., Fujiwara, Y., Kida, K., 1999. Pilot plant test for removal of organic matter, N and P from whisky pot ale. Process Biochem. 35, 267–275.

WEW Engineering, 2019. URL (accessed 11.16.20). https://wewengineering.ie/projects/slane-whiskey-distillery/.

Wood, K., 2015. Roseisle Distillery Info and Tasting Notes [WWW Document]. URL (accessed 5.8.21). http://www.whisky-emporium.com/UK/ActualTastingNotes/Roseisle.htm.

Zheng, Y., Zhao, J., Xu, F., Li, Y., 2014. Pre-treatment of lignocellulosic biomass for enhanced biogas production. Prog. Energy Combust. Sci. 42, 35–53.