



## REVIEW ARTICLE

# A Review on Bioethanol Production through the Valorization of Food Waste in Indonesia

**Tifara Elaine Trisna<sup>1</sup>, Jyotsna Jai<sup>1</sup>, Deborah Shirleen<sup>1</sup>, Ryan Matthew<sup>1</sup>, Katherine<sup>1\*</sup>**

<sup>1</sup>Department of Biotechnology, Institut Bio Scientia Internasional Indonesia, Jakarta, Indonesia

\*corresponding author: [katherine.k@i3i.ac.id](mailto:katherine.k@i3i.ac.id)

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## ABSTRACT

Biofuels are one of the numerous alternatives currently being considered to replace fossil fuels as they are more environmentally friendly. Specifically, bioethanol is often thought of as a better alternative to gasoline fuel as it is considered cleaner, more renewable, and greener as it is synthesized from renewable feedstock, which contributes to the reduction of greenhouse gas emissions to the environment. As bioethanol is produced from carbohydrate and starch-rich food crops, food waste (FW) poses a potential source for bioethanol production as it is especially rich in carbohydrates and lipids. Bioethanol production itself consists of several steps, which include food waste selection, pretreatment, saccharification and fermentation, and recovery. First, cafeteria FW was reviewed to be the best type of FW for bioethanol production as it has the highest carbohydrate and starch content. Subsequently, acid pretreatment was considered to be the best method due to its low cost, high yielding, and time-efficient method. Moreover, the non-isothermal simultaneous saccharification and fermentation (NSSF) produce 1.42 g ethanol/L.h within a time of 38 hours. Lastly, the enzyme-assisted extraction technique is most preferred to recover the bioactive compounds as it leads to the highest yield of product (94%) compared to other methods.

## KEYWORDS

*Bioethanol; Food Waste; Saccharification; Fermentation; Recovery*

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## HIGHLIGHTS

- ❖ Bioethanol is the more renewable alternative to gasoline.
- ❖ Cafeteria mixed food waste contains the most carbohydrates and starch as bioethanol source.
- ❖ Using acid for food waste pretreatment is the most efficient method.
- ❖ NSSF is the most suitable saccharification and fermentation method.
- ❖ Enzyme-assisted extraction yields the most bioactive ethanol product in purification.

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## INTRODUCTION

Humanity's insatiable appetite for fossil fuels as energy artificially amplifies the natural greenhouse effect, leading to a rise in global warming (Shaheen & Lipman, 2007). This rise in fossil fuel depletion and the temperatures of the Earth's atmosphere is caused by global warming, majorly due to the emission of greenhouse gases arising from fossil fuel combustion. This sparked an interest in the field of scientific research to search for alternative fuels that are more environmentally friendly. Biofuels serve as one of the numerous alternatives that are currently being considered. Biofuels refer to fuels in the liquid, solid or

gaseous form that are produced by converting feedstock, including forest biomass (wood species found in short rotation forestry), agricultural residues, energy crops of either annual or pluriannual species, as well as processed biomass wastes (sewage sludge, manure, municipal solid waste, food waste) (Maucieri et al., 2019).

Bioethanol, specifically, is thought of as the most promising alternative capable of replacing gasoline, majorly due to the fact that it is considered to be cleaner, more renewable, and greener (Thangavelu et al., 2016). Since it is synthesized from renewable feedstock, bioethanol production leads to the formation of little to no net carbon dioxide, thus contributing to the reduction of greenhouse gas emissions to the environment. Specifically, the feedstocks utilized to generate biofuels are classified into three categories: first-, second-, and third-generation feedstocks (Jeswani et al., 2020). First-generation feedstocks include food crops, whereas second-generation feedstocks include energy crops and waste, including food waste. Lastly, microalgae are classified as third-generation feedstocks. First-generation biofuels are usually referred to as conventional biofuels due to their utilization of well-established processes and technologies. However, second- and third-generation biofuels are referred to as advanced biofuels as the processes and technologies utilized are still under research and development. Due to this, most bioethanol in the market is conventional bioethanol. Further, Dahmen et al. (2019) suggest that bioethanol is biodegradable and oxygenated, which provides the potential to reduce emissions from automobiles and also contains high levels of octane, which allows for a significantly great compression ratio, leading to a rise in the efficiency as well as the performance of the engine. Another significant advantage of bioethanol is the ease with which it can be integrated into the existing road transportation fuel system. Bioethanol may be blended with conventional fuels (up to 15%) without requiring engine modifications (Ryan et al., 2006). Pertamina, Indonesia's national energy company, reported that approximately 1.4 million barrels of fuel were consumed per day, with the national production being only about 850,000 barrels. This indicates that the remaining 550,000 (40%) supply is imported (Maryana et al., 2021). Owing to this concern, the government launched a commitment in 2014 (regulation No.79 on National Energy Policy), to employ a more renewable form of energy in the form of bioethanol. In 2015, Indonesia was capable of producing only about 450 million liters of this form of renewable energy using sugarcane molasses, which was equivalent to only 1% of the total gasoline usage in 2015, which eventually rose to approximately 8% in 2017, and to 9% in 2019 (Khatiwada & Silveria, 2017). However, the government aims to increase this amount to at least 23% by 2025 and 31% by 2050.

Nevertheless, despite the advantages explained above, the use of bioethanol as an alternative fuel also puts forward a certain issue. Bioethanol is not as economically feasible compared to gasoline fuels yet, and a lot is left to work on in order to decrease production costs. There are various cost constraints involved in the production of bioethanol, including the enzymes used, costs related to detoxification as well as recovery of ethanol (Sindhu et al., 2019). Moreover, the revenue streams prepared for creating cellulosic ethanol are primarily influenced by the pretreatment process since it needs some process to deconstruct the complex biostructure biomass structure (Vadlani, 2020). Additionally, the cost of bioethanol also greatly depends on the cost of the feedstock used. For instance, in Indonesia, the cost of molasses increases annually, where it was about IDR 1,863 from November 2019 to March 2020 per kg, as 1 L of bioethanol involves the use of 4 kilograms of molasses, the cost of 1 L of bioethanol is IDR 7,452 (4 x molasses cost/kg) (Maryana et al., 2021). Moreover, bioethanol is produced mainly from carbohydrate and starch-rich food crops such as corn, sugar cane, wheat, sugar beets, et cetera. Therefore, its production takes up land that could have been used to grow food, which has been criticized for causing the rise in food prices (Loizidou et al., 2017). This explains why the use of petroleum products is still preferable to that of biofuels in many countries, including Indonesia, as the process of producing bioethanol is more expensive, resulting in a higher selling price as well.

Since bioethanol can be produced from different kinds of sugars, food waste which is rich in sources of carbohydrates, lipids, phosphates, as well as amino acids can be used as a source of sugar for the synthesis

of biofuel. Therefore, this review aims to compare different methods used to process food waste in order to determine which ones are the most suitable and efficient for the valorization of food waste to produce bioethanol. Therefore, this review will first cover an introduction to food waste in Indonesia, along with its advantages and disadvantages in producing bioethanol, followed by the upstream (selection, pretreatment, saccharification and fermentation) and downstream (recovery) processes involved in the production of bioethanol.

## FOOD WASTE

Food waste (FW) is commonly produced in kitchens, restaurants, agricultural fields, food processing plants, industries, and markets, among other places. FW accounts for about a third of all municipal garbage. The FW is collected and unloaded to be incinerated or landfilled without any proper pretreatment before disposal (Kumar et al., 2016). This could have a number of harmful consequences for the ecosystem. Incineration of FW, for example, results in air pollution and the discharge of ash and flue gas into the atmosphere and can lead to a variety of pulmonary issues in individuals handling FW incineration (Karmee & Lin, 2014). Moreover, about 6% of damaged food in FW produces a pungent odor as it decomposes (Carroll et al., 2020). Similarly, landfilling of FW produces harmful by-products such as landfill leachates, which contaminate groundwater and also result in the release of additional corrosive gases, including methane and hydrogen sulfide (Kavitha et al., 2020). Therefore, the valorization of food waste in the production of bioethanol can help to solve this issue.

### Food waste in Indonesia

Inefficient processing, transportation, storage, and wastage at the consumer level have resulted in Indonesia throwing away around 23 to 48 million metric tons of food every year (FAO, 2015). As a matter of fact, the amount of food loss reached approximately 115-184 kilograms per capita per year between 2000-2019 (FAO, 2015). Particularly, the biggest contribution to Indonesia's food waste occurs in the consumption stage, in which crops (especially cereals) generate the most food waste. The economic loss from food waste is approximately 213-551 trillion rupiah each year, which is equal to 4-5% of Indonesia's Gross Domestic Product (GDP) (Ministry of Environment and Forestry, 2018). Brack et al. (2016) note that with this amount of food waste, 61-125 million people (29-47% of Indonesia's population) can be fed. In addition to the loss faced by the food wasted by the country, FW often ends up in landfills, where they contribute to approximately 29% of the country's greenhouse gas emissions. According to Brack et al. (2016), the total amount of greenhouse gas emissions that resulted from food loss and waste was 1,703 megatons of carbon dioxide (equivalent to 20 years).

### Advantages and disadvantages of food waste valorization for bioethanol production

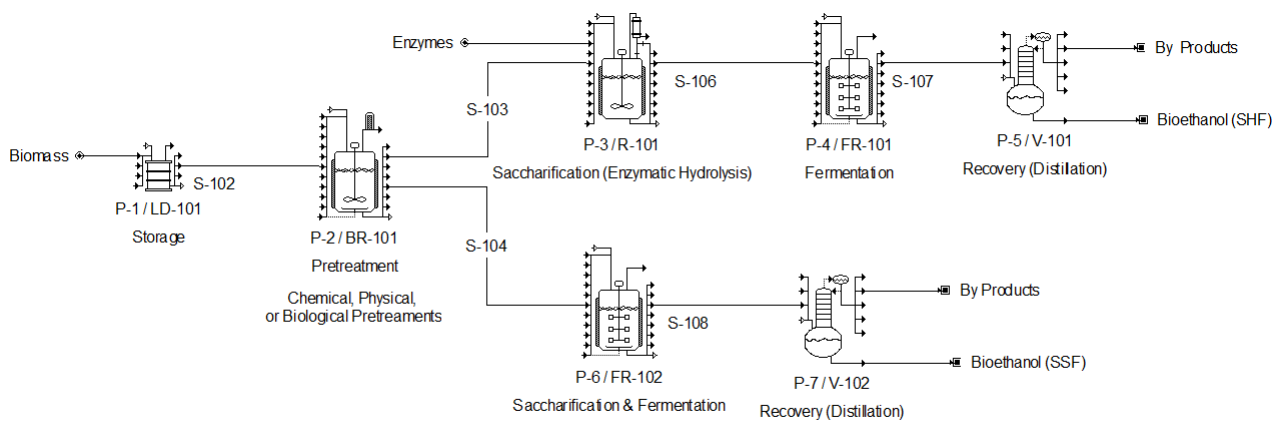
The valorization of food waste for the production of bioethanol confers various advantages. Firstly, FW quickly degrades when compared to other organic waste (Kavitha et al., 2020). Additionally, the feedstock itself can be obtained easily from various food items, including sugar beet, bagasse, switchgrass, grain, sugar cane, molasses, potatoes, barley, wheat, stover, corn, et cetera, that are rich in carbohydrates (Karmee & Chadha, 2005). Not only the production process but the concept of bioethanol itself also promotes a greener approach to both fuel production and food waste management, thus supporting the eco-friendly lifestyle. (Wang et al., 2016).

The production of bioethanol from the valorization of food waste puts forward several advantages; however, the production method also brings some drawbacks. The high production cost is one of the main drawbacks hindering this process's application (Saeed et al., 2018). Particularly, the different cost constraints involved in this are the cost of the enzymes used, costs related to detoxification as well as recovery of ethanol

(Sindhu et al., 2019). Therefore, advanced and economical valorization methods are still to be developed to provide a cost-effective production method capable of dealing with the diverse nature of food waste (Carrillo-Nieves et al., 2019).

## BIOETHANOL PRODUCTION

A typical bioethanol conversion relies on enzymes for converting biomass to ethanol and is done through this series of steps: food waste selection, pretreatment, saccharification and fermentation of the resulting sugars into ethanol, and purification (Rastogi & Shrivastava, 2017; Sabiha-Hanim & Halim, 2019). As seen in Figure 1, the schematic diagram represents the cradle-to-gate bioethanol production process. This process itself may vary according to the biomass feedstock utilized. However, the overall process of bioethanol production would remain the same regardless of utilizing first, second, or third generation biomass feedstock (Jeswani et al., 2020). This includes storage of selected biomass, pretreatment of biomass, saccharification and fermentation, and recovery of bioethanol (Niphadkar et al., 2018).



**Figure 1.** Schematic representation of bioethanol production using separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) (Niphadkar et al., 2018; Guragain et al., 2016; Jeswani et al., 2020)

## Food waste selection

Although food waste poses a great source for bioethanol production, this source highly varies depending on the area, season, and dietary habits of the citizens (Prasoulas et al., 2020). However, the composition of food waste is rich in carbohydrates, proteins, lipids and minerals, valuable sugars, starches, cellulose, hemicellulose, and many more compounds that make food waste an ideal raw material for the production of bioethanol (Loizidou et al., 2017). The availability of nutrients, including sources of carbon, nitrogen, vitamins, and lipids, is necessary for the fermentation of ethanol. Glucose (and its more complex substrates like carbohydrates and starch) serves as the carbon source for ethanol production. This conversion can be divided into two steps: glycolysis, which breaks down glucose into pyruvates, and fermentation under anaerobic conditions that changes pyruvate into alcohol (Kang & Lee, 2015). While the protein serves as a nitrogen source after biodegradation (Uçkun Kiran, 2014), lipids play an important role in adaptation to fermentation stress (Girardi Piva et al., 2022). Therefore, this proves that a food waste selection step is needed prior to entering any of the bioethanol production steps.

**Bakery waste (Cake waste).** Research conducted by Uçkun Kiran and Liu (2015) used bakery waste, such as cake waste, as the sole substrate of bioethanol production. The wastes were collected from a local catering and were ground, sieved, and stored at -20°C. The waste was then analyzed to result in 64.3%, 45.8%, 14.1%, 16.1%, and 3.9% (w/w, dry basis) of carbohydrates, starch, protein, lipids, and ash respectively (Table

1). The starchy substance in bread is a rich and pure supply of fermentable sugars that are simple to extract. Unfortunately, the relatively short material lifetime, strict procedural, and hygiene standards limit the opportunities for direct recycling of bread trash within the food business. Common techniques for valorizing bread trash include anaerobic digestion (AD) and incineration (Narisetty, 2021).

**Cafeteria mixed FW.** Another research done by Uçkun Kiran and Liu (2015) utilized a mixed FW that was gathered from the cafeteria at Nanyang Technological University, Singapore. It was then homogenized in a blender and was stored at -20°C. The composition of the mixed FW is shown in Table 1 with 76.8%, 60.3%, 8.6%, 14.6%, and 2.9% (w/w, dry basis) of carbohydrates, starch, protein, lipids, and ash, respectively.

**Household food waste (HFW).** HFW possesses various valuable components which provide sources of potential fermentative substrates, including soluble sugars, starches, proteins, lipids, cellulose, et cetera. In accordance with the research carried out by Loizidou et al. (2020), HFW was gathered from households in Aspropyrgos Municipalities and Papagos-Cholargos, Athens, Greece. The HFW was then fed to a decentralized biowaste dryer which significantly reduced its volume and mass. The low moisture content will also facilitate the preservation of the fermentable sugars present in the sample by inhibiting microbial activity. The resulting food waste shows w/w dry basis content of carbohydrates (36.94%), starch (16.81%), protein (15.75%), lipids (3.93%), cellulose (12.01%), hemicellulose (5.58%), and ash (3.21%).

**Analysis of FW types for bioethanol production.** As seen in Table 1, the FW type containing the highest amount of carbohydrates and starch is the Cafeteria Mixed FW with the lowest amount of ash. Meanwhile, the highest protein content is found in HFW, and the highest lipid content is found in Bakery Wastes. As bioethanol is currently made from sugars and starch-rich food crops such as corn, sugar cane, sugar beets, barley, and corn, therefore the most important content needed for bioethanol production are carbohydrates and starch (Loizidou et al., 2017). Thus, the best FW used for bioethanol production is the Cafeteria Mixed FW. This FW source also requires simple pretreatment and provides a sufficient amount for its conversion.

**Table 1.** Evaluation of quantity, issues and composition of FW Types in % (w/w, dry basis)

FW Type	Quantity (kg/capita/year)	Transportation issue or pretreatment requirement	Carbohydrates <sup>a</sup>	Protein	Lipid	Ash	Reference
Bakery Wastes	13 (UNEP, 2021)	Must be transported fast and require anaerobic digestion treatment (Narisetty et al., 2021)	64.3	14.1	16.1	3.9	(Uçkun Kiran & Liu, 2015)
Cafeteria Mixed FW	26 (UNEP, 2021)	Physical mixing pretreatment (Uçkun Kiran & Liu, 2015)	76.8	8.6	14.6	2.9	
HFW	79 (UNEP, 2021)	Physical pretreatment, such as milling and grinding (Bernstad et al., 2013)	71.3	15.75	3.93	3.21	(Loizidou et al., 2017)

<sup>a</sup>the total carbohydrates are composed of reducing sugars including glucose, starch, fructose, sucrose, cellulose, hemicellulose

**Pretreatment**

Pretreatment aims to increase the fermentable monosaccharide sugar production by altering the FW structure either physically, chemically or biologically; thus, the enzyme has more access to it (Prasoulas et al., 2020). Different methods will generate different efficiency, by-products, cost, energy demand, and wastewater treatment systems (Alvira et al., 2010). Physical pretreatment involves ultrasonic, hydrothermal,

milling or grinding to crush the FW, thereby increasing the contact area. Chemical pretreatment with diluted acid (oxalic-, sulphuric-, and maleic acid) or mild alkali (potassium-, ammonium-, and sodium hydroxide), the most conventional method on an industrial scale, is useful for unraveling the polysaccharide network. Biological pretreatment calls for microorganisms such as fungi to break down the FW (Rastogi & Shrivastava, 2017). These methods are not only used solely on their own but are commonly combined to achieve maximum pretreatment. In this pretreatment section, the results presented are taken after the saccharification. An appropriate pretreatment method should have the following criteria: energy, time and cost-effectiveness and generate a high value of glucose product.

**Ultrasonic pretreatment.** Mechanical pretreatment is normally performed prior to every FW treatment and also usually complements another pretreatment. Physical destruction is critical for the subsequent steps to break down and homogenize ingredients. Physico-chemical is the most common form used in pre-treating biochemical sources. Mechanical disk millers, bead mill homogenizers, and high-pressure homogenizers are examples of machines able to perform mechanical pretreatment besides ultrasonic (Kumar & Sharma, 2017). High-intensity ultrasound (20 kHz) was used to pre-treat the FW; the acoustic cavitation treatment thus results in high shear forces (Chatel & Colmenares, 2017; Khanal et al., 2017; Kuna et al., 2017) that can help in mixing, mass transfer, and particle breakup (Ashokkumar et al., 2011). When the power intensity of ultrasonic technology was enhanced by increasing the size of the energy-emitting-horns, it improved its efficiency on FW. For samples pre-treated with ultrasound, the hydrolysis rate was greatly increased, and the time necessary to reach high yields was cut in half. For effective sonication, the procedure was performed for 5 minutes with a 13W/mL higher-power density level using the 11 mm horn and the temperature was maintained at 20°C to keep the nutrients in food waste undamaged (Li et al., 2019).

**Fungal mash pretreatment.** In-situ production of a fungal mash rich in hydrolytic enzymes was achieved using waste cake. The fungal mash could then be obtained at the end of the fermentation and directly employed to hydrolyze the mixed FW in the bioreactor. The reaction was carried out at 60 °C with a mixing speed of 500 rpm for 24 h. During the hydrolysis, the pH was in the range of 4.0–4.5; therefore, it was not controlled. The hydrolyzate produced from the enzymatic pretreatment by mixing the FW with the fungal mash proves to be a suitable bio medium for the next ethanol fermentation. The fungal mash produced, rich in carbohydrases with highly active  $\alpha$ -amylase,  $\beta$ -glucosidase, cellulase, glucoamylase, and xylanase, will hydrolyze cellulose and release glucose (Uçkun Kiran & Liu, 2015).

**Acid pretreatment.** Acid pretreatment is commonly done at either a high (> 180°C) or a low (120°C) temperature for short or extended periods of time, respectively. Disintegrating agents used normally are diluted acid (sulphuric acid, oxalic and maleic acid) (Rastogi & Shrivastava, 2017). The biopolymer cellulose is made up of numerous glucose units united by 1,4-glycosidic linkages. The hydrolysis of cellulose polymers occurs when acids break the 1,4-glycosidic linkages, resulting in the sugar molecule glucose or oligosaccharides (Dussan et al., 2014). Because of its low cost and the availability of the acids utilized, acid pretreatment is a widely used technology for biomass to ethanol conversion (Sabiha-Hanim & Asyikin, 2019). On the other hand, acid pretreatments might have negative consequences, such as the generation of furan and short-chain aliphatic acid derivatives, potent inhibitors of microbial fermentation (Hendriks & Zeeman, 2009; Kumar et al., 2009). Because sulfuric acid ( $H_2SO_4$ ) is relatively inexpensive and effective at hydrolyzing cellulose, they are commonly employed for acid pretreatment (Canilha et al., 2011; Zhao, Zhou & Liu, 2012). In Alamanou et al. (2015), they combined drying, milling, giving hydrothermal treatment and acidifying the FW. FW was dried with a bio-waste dryer and milled into < 3 mm in a laboratory mill. The dried FW are then submerged in hot water at 100°C for 60 min in the presence of 1 g sulfuric acid/100 g of dry HFW.

**Alkali pretreatment.** Alkali promotes cellulose accessibility by disturbing cellulose crystallinity and eliminating non-cellulosic components (Bali et al., 2014). Mild alkali (sodium hydroxide, potassium hydroxide and ammonium hydroxide) is commonly used. Hydroxides are inexpensive; however, they require a large amount of water to wash the sodium (or calcium) salts that are incorporated into the material, making

alkaline pretreatment of large amounts of salts difficult. During the process, certain enzyme inhibitors can also be produced (Chaturvedi & Verma, 2013). Alkali pretreatment often employs lower pressures, temperatures, and surrounding conditions compared to other pretreatment processes. On the other hand, the pretreatment time performed at low temperatures is significantly longer than any other pretreatment methods, such as 24 hours or days (Sabiha-Hanim et al., 2012). Preheated 4% NaOH of 55°C was gradually mixed into the FW contained in the reactors. The reactor was capped tightly and then incubated in an isothermal incubator at 55°C for 3 hours (Cheng et al., 2010).

**Table 2.** Comparative Analyses of Different Pretreatment Methods After the Hydrolysis

Pretreatment	Cost	Conversion Efficiency	Glucose Concentration (g/L)	Volumetric productivity of glucose (g/L.h)	Advantages	Disadvantages	Reference
Ultrasound	High	+10%	76.4	916.8	Chemical-free, safe, performed in a short period	High initial investment & may induce starch gelatinization	(Li et al., 2019)
Fungal Mash	Lowest	+98%	127	5.292	Cost and energy efficient, eco-friendly	Exhibits unstable activity & is dependent on various factors	(Uçkun Kiran & Liu, 2015)
Acid	Low	+58.39%	31.03	31.03	Cheap and readily available reagents, powerful agents for cellulose hydrolysis	Requires inhibitor removal, produces a considerable amount of recalcitrant, corrosive & involves high temperatures	(Alamanou, 2015)
Alkali	Low	+39.2%	9.27	3.09	Cheap and readily available reagent, mild temperature operations	Requires inhibitor removal & produces a considerable amount of recalcitrant	(Cheng et al., 2010)

Reviewing the cost, conversion efficiency, yield, titer, productivity, and other considerations listed in Table 2, it is agreeable that each method has its own drawbacks and things to appraise. Physical and mechanical pretreatment procedures, in particular, consume much energy and produce a lot of refractory chemicals when compared to other approaches. Other than that, ultrasonic pretreatment is also at a disadvantage due to its high price and minimum conversion efficiency - even though it has the highest productivity due to the short process time (5 minutes). Biological pretreatment is the most cost-effective option compared to other treatments since it uses less energy and is environmentally benign (Yukesh Kannah et al., 2020). Fungal mash was recently claimed to be effective by Uçkun Kiran and Liu (2015), and by titer, it

does generate significantly higher glucose concentration than the other, but low productivity since it is produced in 24 hours' time. Chemical pretreatment needs considerable capital expense due to its additional step of inhibitor removal. In consideration of the low cost, high conversion rate (59%), and moderate time (1 h) - acid pretreatment is the most effective method.

### Saccharification and fermentation

Following the pretreatment process, where the samples' digestibility was increased, and bioethanol production took place, is the saccharification and fermentation process (Loizidou et al., 2017). This process aims to liberate the monosaccharides, converting cellulose into glucose by the utilization of enzymatic hydrolysis, where it will be converted into ethanol by microorganisms' activity during the fermentation process (Triwahyuni et al., 2015). Therefore, the expected result of this process is the ethanol itself deliberated from the samples with high ethanol yield. The saccharification and fermentation process could be done in many ways, either separately or simultaneously; thus, the final result of each process could also vary. This subpart of the paper will talk about the various methods that could be used for saccharification and fermentation and as well as compare them to find the most suitable and efficient method for utilization in terms of bioethanol productivity and yield.

**Separate hydrolysis and fermentation (SHF).** SHF involves two subsequent consecutive steps, including enzymatic saccharification and fermentation that will allow both processes to be done within optimal operating conditions for both the enzymes and the microorganisms (Triwahyuni et al., 2015). Within the study conducted by Uçkun Kiran and Liu (2015), FW hydrolysis and ethanol fermentation were conducted separately where the hydrolyzate was first made and thus combined with yeast for fermentation anaerobically. The hydrolyzate resulted in a glucose concentration of 127 g/L after 24 hours, and the bioethanol resulted in the highest concentration of 58 g/L after 32 hours with 98% of the theoretical ethanol yield. Thus, combining both the saccharification and fermentation process, the production took 56 hours to complete.

**Simultaneous saccharification and fermentation (SSF).** With the SSF process, hydrolysis glucose production and fermentation are metabolized simultaneously by microorganisms producing ethanol which would alleviate problems associated with product inhibition (Triwahyuni et al., 2015). This process may reduce fermentation time, reducing capital costs but also increase the rate of hydrolysis, which leads to improved productivity and product yield (Jugwanth et al., 2019). However, one step within the bioethanol production, which fluctuates the cost is the enzymatic hydrolysis or the saccharification step that requires different enzymes to break down cellulose to glucose. There were two proposed steps that were mentioned in order to decrease the production cost of bioethanol, including using cheap and abundant substrates or using on-site production of relevant enzymes instead of using commercially available enzymes.

*SSF with readily available enzymes.* The study conducted by Febrianti et al. (2017) uses *Aspergillus niger* and *Saccharomyces cerevisiae* without the utilization of synthetic enzymes. *A. niger* itself serves as a saccharification agent converting starch into sugar; subsequently, the sugar is fermented into bioethanol by the *S. cerevisiae*. The cultivation of *A. niger* produces hydrolysis enzymes such as amylase, invertase, and glucoamylase. Additionally, it could produce cellulase enzymes as well. The fermentation was conducted in batch fermentation which was said to be more effective at producing bioethanol without adding enzymes or replacing microbes at each stage of the process. The study then resulted in a maximum concentration of bioethanol after 72 hours at 7.69 g/L.

*SSF with on-site production of relevant enzymes.* On the other hand, the study conducted by Prasoulas et al. (2020), used mixed *Fusarium oxysporum* and *Saccharomyces cerevisiae* cultures. The *F. oxysporum* itself was mentioned to be used for ethanol production and cellulolytic enzyme production as it could ferment both hexoses and pentoses, thus increasing ethanol production. The on-site production of enzymes was done with the solid-state cultivation (SSC) process, which was then combined with the SSF of



the food wastes. SSC itself makes the production process have higher fermentation capacity, lower catabolic repression, cost-effective technology, and higher end-product stability. This is due to the solid substrate, which has similar characteristics to the natural habitat of the fungi, thus improving the growth and secretion of various enzymes. Through the study, the highest bioethanol production was reached after 69 hours at 30.8 g/L with a volumetric productivity of 1.4 g/L/h.

**Non-isothermal simultaneous saccharification and fermentation (NSSF).** NSSF is done with a pre-hydrolysis step with an optimum temperature well suited to the enzymes, followed by the fermentation process (Loizidou et al., 2017). The pre-hydrolysis itself enhances saccharification; however, it would require more time, energy, and operational unit. Through the NSSF process, a high efficacy for enzymatic hydrolysis and fermentation within the optimum conditions could be achieved utilizing a non-isothermal temperature set (Wang et al., 2020). The process itself uses a fed-batch fermentation process which is done to alleviate mixing problems of high initial substrate concentration, thus increasing ethanol titer (Fan & Lynd, 2007; Jørgensen et al., 2007). Through the study, the maximum ethanol concentration acquired was 53.90 g/L after 38 hours, with a yield of 0.15 g/g and a maximum theoretical percentage of 73.26%.

### Comparison of saccharification and fermentation processes

Previously, several methods of saccharification and fermentation were discussed, including separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SFF), and non-isothermal simultaneous saccharification and fermentation (NSSF). As seen in Table 3, all of the saccharification and fermentation processes were done at 30°C with anaerobic conditions. The SHF process was done in batch fermentation utilizing *Aspergillus awamori* for hydrolysis and *Saccharomyces cerevisiae* for fermentation. Hydrolysis was done at a pH ranging from 4.0 to 4.5 in 60°C, whereas the fermentation pH was not reported. The SSF process with readily available enzymes used batch fermentation with *Aspergillus niger* and *Saccharomyces cerevisiae*, and the pH was not reported as well. In contrast, the SSF process with on-site production of relevant enzymes was done in batch fermentation with *Fusarium oxysporum* and *Saccharomyces cerevisiae*, with a pH of 6.0. Lastly, the NSSF process was done in fed-batch fermentation with only *Saccharomyces cerevisiae* at a pH of 5.0.

In Table 4, the result of bioethanol from each of the processes was listed, including the ethanol concentration, ethanol yield, volumetric productivity of ethanol, the percentage of the maximum theoretical, and the time for the process to happen, resulting in the maximum ethanol concentration. The final ethanol concentration showed that the SHF process resulted in the highest concentration, followed by the NSSF. When comparing the ethanol yield, it could be seen that SHF has the highest yield, followed by SSF with readily available enzymes. Whereby the volumetric productivity of the ethanol was the highest using the SHF process and followed by NSSF the second. As for the percentage of the theoretical maximum, SHF has the highest percentage of 98%, followed by SSF with readily available enzymes with a percentage of 88%. As for the time spent, SSF with readily available enzymes took the longest, with 72 hours to reach maximum production, followed by SSF with on-site enzyme production with 69 hours to reach maximum production.

However, the ethanol concentration itself could not determine the efficacy of the process for the amount of sample and substrate used to differ in each study. With all the variables, starting from the yield to the time the process took to complete, it could be concluded that SHF produces the highest yield with the highest productivity and the highest percentage of the theoretical yield. This would be due to the utilization of two bioreactors which optimizes the temperature and conditions for each of the processes, although it would double the cost of production (Jugwanth et al., 2019; Wang et al., 2020). Following SHF, NSSF could be concluded to have produced the second highest ethanol yield with the second-highest volumetric productivity and a high percentage from maximum theoretical with the lowest time to complete the process. However, the NSSF process needs additional time, energy, and operational units due to the pre-hydrolysis step before the saccharification and fermentation process. The SSF processes have a higher yield and

percentage of theoretical yield, and require less cost due to no pre-hydrolysis step or need two bioreactors, but the productivity is relatively low compared to SHF and NSSF. Additionally, the time required for the process doubles the time required for NSSF. Thus, the most suitable and efficient process for the saccharification and fermentation of food waste is the NSSF process considering the volumetric productivity, the time required, and ethanol yield.

**Table 3.** Fermentation Parameters of Saccharification and Fermentation Processes

Saccharification & Fermentation Process	Fermentation Process	Microbes Used	pH	Temperature (°C)	Oxygen supply	Reference	
SHF	Hydrolysis	-	<i>Aspergillus awamori</i>	4.0-4.5	60	-	(Uçkun Kiran & Liu, 2015)
	Fermentation	Batch Fermentation	<i>Saccharomyces cerevisiae</i>	NR	30	No	
SSF with Readily Available Enzymes	Batch Fermentation	<i>Saccharomyces cerevisiae</i> & <i>Aspergillus niger</i>	NR	30	No	(Febrianti et al., 2017)	
SSF with On-site Production of Relevant Enzymes	Batch Fermentation	<i>Fusarium oxysporum</i> & <i>Saccharomyces cerevisiae</i>	6.0	30	No	(Prasoulas et al., 2020)	
NSSF	Fed-Batch Fermentation	<i>Saccharomyces cerevisiae</i>	5.0	30	No	(Loizidou et al., 2017)	

NR: Not Reported  
 -: not applied

**Table 4.** Bioethanol Products Resulting from Different Saccharification and Fermentation Processes

Saccharification & Fermentation Process	Ethanol Concentration (g/L) <sup>a</sup>	Ethanol yield (g ethanol/g substrate) <sup>b</sup>	Volumetric productivity of ethanol (g/L.h) <sup>c</sup>	The percentage from maximum theoretical (%) <sup>d</sup>	Time (hours) <sup>e</sup>	Cost	Reference
SHF <sup>f</sup>	58	0.5	1.82	98%	56 <sup>g</sup>	High	(Uçkun Kiran & Liu, 2015)
SSF with Readily Available Enzymes	7.69	0.23	0.11	88%	72	Low	(Febrianti et al., 2017)
SSF with On-site Production of Enzymes	30.8	0.11	0.44	51%	69	Low	(Prasoulas et al., 2020)
NSSF	53.90	0.15	1.42	73.26%	38	High	(Loizidou et al., 2017)

<sup>a</sup>bioethanol produced from the process

<sup>b</sup>bioethanol produced per 1 gram of substrate

<sup>c</sup>volumetric productivity = ethanol concentration/time

<sup>d</sup>percentage of maximum theoretical = (ethanol produced in fermentation/theoretical amount of ethanol produced) x 100%

<sup>e</sup>total time need to complete both saccharification and fermentation process

<sup>f</sup>FW was pre-treated by *in-situ* produced fungal mash

<sup>g</sup>combination of saccharification and fermentation process, excluding preparation time

### Bioethanol recovery

Bioethanol obtained after fermentation is in an aqueous mixture, from which water must be removed to obtain a high purity yield (greater than 99 wt%) of anhydrous bioethanol (Segovia-Hernández & Mendoza-Pedroza, 2018). This is because it is in the anhydrous form in which bioethanol can be employed for the purpose of a biofuel. Ethanol recovery and dehydration generally occur through the distillation of the fermented broth. In contrast, dehydration is generally performed using techniques such as extractive distillation (the utilization of solvents for modifying the relative volatility of bioethanol in order to achieve the desired extent of separation) as well as azeotropic distillation (Kissa & Suszwalak, 2012; Segovia-Hernández & Mendoza-Pedroza, 2018) evaporation and adsorption (Frolkova & Raeva, 2010; Gil et al., 2008; Segovia-Hernández & Mendoza-Pedroza, 2018). Distillation is a relatively energy-intensive process that is utilized for the purpose of separating ethanol from fermented broths and covers a large proportion of the cost of producing bioethanol (Gavahian et al., 2018; O'Brien et al., 2000). According to Gavahian et al. (2019), dehydration is a process in which great quantities of energy are required, majorly due to the challenge faced during the separation of the ethanol-water mixture. In fact, the greatest challenges involved in bioethanol dehydration are the attempt to decrease the thermal energy used, requirements, operation costs as well as the emission or involvement of pollutants as much as possible. Broth bioethanol generally consists of more than 80 wt% of water, implying that high quantities of energy would be needed in order to concentrate the bioethanol to a purity of 99.5 wt% (Gavahian et al., 2019). Ethanol is concentrated to its azeotropic point (with water), approximately 95% ethanol, through conventional distillation, which could be called hydrated or hydrous ethanol. In contrast, when continuously dehydrated, azeotropic ethanol leads to the formation of "anhydrous" alcohol (99.6% ethanol). An azeotrope (commonly referred to as a constant boiling point mixture) is a mixture of two or more liquids in which the quantity of each cannot be varied through the use of conventional or simple distillation (Gavahian et al., 2019). Additionally, the ability to recover ethanol with a low energy efficiency characteristic of conventional distillation columns is limited by the formation of an azeotrope with water (Gavahian et al., 2019; Olujic et al., 2009).

Despite the drawbacks of distillation and dehydration, they are important operations for bioethanol processing. Therefore, various energy-saving alternative approaches are proposed, most of which work on the basis of the physicochemical properties of the mixture between ethanol and water as well as the equipment configurations. The proposed alternatives include membrane-based, heat-integrated, ohmic-assisted, and feed splitting methods of distillation, as summarized in Table 5.

**Heat integrated distillation.** Heat integrated distillation is a method that can improve the utilization of initial energy that is applied to the distillation system. Several studies carried out employing this technique showed that the energy consumption for the production of biofuel was reduced by up to 40% (Dias et al., 2011; Dias et al., 2012; Diaz & Tost, 2016; Gavahian et al., 2019). In addition, the possibility of decreasing energy consumption through the use of different devices, including multiple-effect columns, heat pumps, heat exchangers, and adiabatic columns, was also studied. Due to this, Dias et al. (2009) evaluated a double-effect distillation system applied to a conventional bioethanol plant. The authors employed a combination of sugarcane extract and bagasse as the feedstock for producing ethanol. This experiment resulted in a 26% increased bioethanol production double-effect system from 102.5 L (along with 33.0 kW h/t of sugarcane) to

105.7 (along with 13.5 kW h/t of sugarcane) L per ton of sugarcane of anhydrous ethanol produced by only using 10% of the sugarcane bagasse to fuel the system. This proves that the double-effect system increases bioethanol production. Furthermore, in another study conducted by Dias et al. (2011), the authors revealed that double-effect distillation is also capable of reducing the amount of steam used in bioethanol production.

Conventionally, the biotechnological approach for the production of ethanol involves the fermentation process. ABE, which is referred to as a mixture of acetone butanol and ethanol and can be utilized as a biofuel, is the outcome of the fermentation stage. According to Qureshi et al. (2005), this mixture is of relatively low concentration in the fermented biomass (15–30 g L<sup>-1</sup>), thereby making ABE recovery an energy-intensive process. In fact, the study conducted revealed that approximately 15 MJ of fuel is used for the production of one kilogram of ABE (Qureshi et al., 2005). With this in mind, Diaz and Tost (2016), proposed four different heat-integration distillation processes and evaluated the amount of energy consumed during the fermentation process utilizing various biocatalysts. The results showed that processes composed of four distillation columns required a similar amount of energy as that of three distillation columns (8–12 MJ fuel per kg of ABE). Further, it was revealed that the most economical method is the double-effect system (4 columns), requiring only 6-9 MJ of fuel per kg of ABE.

**Membrane technology.** The utilization of membrane technology for the purpose of ethanol recovery from aqueous solutions works on the fact that ethanol has a higher partial pressure compared to that water. This difference enables ethanol transport to pores of the membrane from the fermented broth. Researchers have also attempted to improve the processes with the aim of accelerating ethanol recovery by decreasing the amount of gas flow or pressure into the permeate part of the membrane. This is called pervaporation, a condition that possesses a concentration gradient across the membrane that serves as the most important aspect for the facilitation of the target compound transport. For the case of membrane-based distillation techniques, the composition of the membrane employed for operation plays a major role in the success of ethanol separation from fermented broths and binary solutions (either from solutions of glucose or fermentable sugars obtained from natural sources) (Gavahian et al., 2019). For instance, Liu et al. (2015) conducted a study that showed a membrane composition of polydimethylsiloxane (PDMS) and ZSM-5 zeolites (Si/Al = 300) was able to result from a 10.0 wt% solution to a 60.0 wt% ethanol solution (under the conditions of 60°C, 2300 Pa, and 80 L h<sup>-1</sup>). Additionally, the column was tested for 1000 h, during which it was observed that the ethanol within the permeate was constant throughout the testing period. Another study conducted by Ueno et al. (2019) employed the use of a silicate-1 membrane led to the production of an ethanol solution that was more concentrated (91.0 wt%). In this study, the membrane system was fed with an ethanol solution of 10 wt% and observed that the efficiency remained constant even after 8 h of the operation (total flow rate of 3 kg/m<sup>2</sup>h at 323 K).

The complexity in terms of the composition of the fermented mixture has encouraged researchers to propose and evaluate various membrane systems for their ability to extract bioethanol through the utilization of glucose solution enriched with nutritional supplements in microbial fermentation as well as in the case of fermented broths of fermentable sugars acquired from different sources. An experiment carried out by Yi & Wan (2017) employed the use of a membrane composed of vinyltriethoxysilane (VTES)-g-silicalite-1/PDMS/PAN for the purpose of separating ethanol which originated from a fermented glucose solution. As a result, the final concentration of ethanol (60.0 wt%) was achieved with a total flow rate of 2.0 L min<sup>-1</sup>, at 210 Pa, at 35°C, for 8 h. Another study conducted by Xue et al. (2016) obtained a lower final concentration of ethanol (38.0 wt%) through the utilization of a carbon nanotube (CNT)/PDMS membrane (total flow of 1.2 L/min, pressure lower than 20 kPa, at 60°C, for 34 h). Promising outcomes from the studies conducted were also obtained in the case of fermented broth for fermentable sugar sources that were more complex in nature. The evaluation of ethanol production and concentration using Jerusalem artichoke tubers by Song et al. (2017) involved the pervaporation of the fermented broth in the PDMS membrane (pressure of 5 mmHg, 1.8 L min<sup>-1</sup> flow) and obtained an ethanol yield of 85.3 wt%. Further, Unlu and Durmaz Hilmioglu (2016)

evaluated the fermentation of molasses and obtained an ethanol yield of 80.0 wt% in the permeate part of the membrane. When Wei et al. (2016) evaluated the utilization of a commercial NaA zeolite membrane for the pervaporation of a fermented broth of rice straw, the authors obtained an ethanol yield of 99.5 wt% (total flow of 6 L/h, pressure of 5-7 bar, and temperature of 100°C).

According to Gavahian et al. (2019), it is challenging to dehydrate purified concentrated ethanol solutions at a yield greater than 95 wt% due to the azeotrope formation with water. However, the utilization of membrane-based technology enables the elimination of water usage in dehydration processes. Another study conducted by Nigiz and Hilmioglu (2016) involved utilizing a carboxymethyl cellulose membrane at a temperature of 25°C, where ethanol production was performed through the fermentation of molasses, which was successful in enhancing the concentration of ethanol from 95 to 98.99 wt%.

*Membrane assisted vapor stripping.* A method that involves the presence of a passage of vapor, which generally originates from water present in the fermented broth containing ethanol solution, for the purpose of volatilizing ethanol is referred to as vapor stripping. Subsequently, separation of the vapor flow into two different flows (the permeate and retentate containing either low or high concentration levels of ethanol, which is dependent on the membrane properties) occurs. In this case, only a few configurations have been proposed till date, including the batch and continuous system. Vane et al. (2010) conducted a study in which the authors evaluated ethanol recovery from an ethanol solution of 5 wt% through the use of a combined system of a hydrophilic membrane and stripping column. The yield obtained a retentate vapor which comprised 80 wt% of ethanol. Vane et al. (2012) conducted a study where the efficiency of ethanol recovery from the fermented broth, which contained 35.9 wt% ethanol, was evaluated. This was performed through the utilization of a membrane made of a hydrophilic cellulose ester layer that was over-coated by silicone rubber after carrying out the vapor stripping step. From this experiment, it was observed that the use of a vapor flow of approximately 0.02-0.06 kmol/h resulted in an ethanol retentate of approximately 90 wt%.

Another study was conducted by Vane et al. (2012), in which the authors recovered ethanol, acetone, and butanol from the fermented broth through the use of a membrane made up of a hydrophilic cellulose ester layer that was over-coated by silicone rubber after conducting the process of vapor stripping. From this experiment, it was revealed that an ABE-rich fraction of 95 wt% was obtained, in which ethanol accounted for approximately 10 wt% in the retentate of the membrane. Furthermore, the authors also revealed that this system could reduce 25% of the energy consumption compared to a simple vapor stripping process. Finally, another study by Xue et al. (2016) involved the evaluation of ABE recovery through the employment of a membrane-assisted vapor stripping system and a comparison to that of the conventional gas tripping pervaporation process. The results obtained suggest that the combined system led to an ethanol yield of 8.3-8.6 g/L. In contrast, the separation of the two techniques led to the production of 7.4-7.7 (gas tripping) and 6.3-6.7 (pervaporation) g/L of ethanol, respectively.

**Feed-splitting.** Feed splitting is a technique capable of improving the energy efficiency of a distillation system, which works with the feed flow being heated by chilling the bottom product flow through a heat exchanger (Gavahian et al., 2019; Soave & Feliu, 2002). However, this method has been explored in only a single study, which proposed that a feed-splitting system could decrease the amount of energy used in the extraction of azeotropic mixes, including the fermented broth used in the biofuel industry (Gavahian et al., 2019; Tavan & Shahhosseini, 2016). The authors conducted the study through the utilization of the Hysys process simulation software as well as optimization analysis, which resulted in an ethanol yield of 99.2% (similar to that of the conventional system), moreover with a 27% reduction in the energy consumed in comparison to the conventional one.

**Ohmic-assisted hydrodistillation.** A system that utilizes an ohmic heater that produces heat in a volumetric manner (as per Joule's law) and a condenser that gathers and condenses the vapor created in the former section is called the Ohmic-assisted hydrodistillation or OAHD (Gavahian et al., 2012). Initially, this

system was intended as an energy-efficient technology for extracting essential oil (Gavahian et al., 2011). The heater is mainly composed of a power supply, electrodes, as well as a non-electroconductive chamber (flask), equipped with extras, namely variable transformers to manage input power, variable transformers and frequency, safety systems, thermocouples, data acquisition systems, voltmeters, et cetera (Gavahian & Farahnaky, 2018; Gavahian et al., 2018). At the same time, the distillation system's condenser section was altered to recover ethanol in place of essential oil. Gavahian et al. (2016) extracted 10% to 47% ethanol from the fermented corn feedstock using this method. In order to produce a higher ethanol concentration method that complies with the ASTM standard, the authors incorporated three successive OAHD processes that effectively increased the concentration of ethanol from 10% to 50%, 76%, and 84% through the use of a voltage value at a fixed wattage of  $168 \pm 5$  W, 3 L of 75% ethanol-water mixture (heated in the apparatus at an initial temperature of  $31 \pm 1^\circ\text{C}$ ) and a continuous heating process till the boiling point reached a value of  $83^\circ\text{C}$ .

**Green extraction of bioactive compounds.** The process of producing bioethanol generally results in numerous amounts of waste together with the resulting by-products, which act as potential nutraceuticals or food additives, such as pectin and bioactive compounds (phenolic compounds) (Gavahian et al., 2019; Granato et al., 2017). For instance, the generation of residues as a result of bioethanol production contains high-added value compounds which possess potential biological activity, namely flavonoids, anthocyanins, and other phenolic compounds, most of which are usually discarded as contaminants. Therefore, tremendous efforts are being made for a "greener" and more "innovative" extraction of bioethanol, enabling the isolation of valuable compounds from the residues generated from bioethanol plants. In turn, these processes can decrease extraction time, temperature, energy and water consumption,  $\text{CO}_2$  emission, and carbon footprint (Clark, 2016; Clark et al., 2016; Gavahian et al., 2019; Misra et al., 2017). Green and innovative technologies, including pulsed electric fields, is the most commonly employed (Gavahian et al., 2019; Puertolas & Barba, 2016), ultrasound (Gavahian et al., 2019; Hashemi et al., 2018; Rosello-Soto et al., 2015), microwaves (Bouras et al., 2015; Gavahian et al., 2019; Koubaa et al., 2016; Sahin et al., 2017), supercritical fluid extraction (Gavahian et al., 2019; Rosello-Soto et al., 2018) and enzyme-assisted extraction (Gavahian et al., 2019; Zhu et al., 2018), all of which will be discussed below and are summarized in Table 5.

*Pulsed electric fields (PEFs).* The utilization of PEFs puts forward the ability to enhance bioethanol recovery (Barba et al., 2015; Gavahian et al., 2019; Puertolas et al., 2016). PEF treatment involves disrupting the natural dipole between two molecules which entrap bioactive compounds, such as bioethanol. In this case, there is an increase in the average distance between membrane components found in living cells, especially those that are linked with transport processes. This occurrence can be explained by the influence of the electric field. Similarly, plant tissues can also undergo disruption, thereby releasing intracellular components (Barba et al., 2015; Gavahian et al., 2019; Putnik et al., 2017). Additionally, several various factors influence PEF, including energy input intensity and field strength, the number of pulses, temperature and treatment time, all of which are of great value in order to improve the extraction yield and extract targeted compounds from a complex matrix (Gavahian et al., 2019; Puertolas & Barba, 2016). Almohammad et al. (2016) conducted a study concerning fermentable sugar extraction for the fermentation of ethanol. The study revealed that the sugar-rich extract obtained from PEF treatment (10 min with an intensity of  $450 \text{ V cm}^{-1}$ ) exhibited a 3.75 yield greater than obtained with solid-liquid extraction (from 21.65% to 79.85%). Therefore, this indicates that the PEF treatment greatly influences the sugar beet matrix employed.

*Ultrasound-assisted extraction.* Cavitation is the phenomenon that is a consequence of the propagation of ultrasound waves in a liquid medium and is caused by the reduction in pressure, which forms vapor cavities. Eventually, these cavities tend to collapse, ultimately creating micro-jetting on the matrix that is subjected to treatment using ultrasound. This will lead to an increase in the interactions between the bioactive compound and the solvent, thereby enabling their recovery (Gavahian et al., 2019; Maric et al., 2018; Rosello-Soto et al., 2015). This is thought to occur as a result of the composition and structure of the

matrix as well as due to the conditions of the ultrasound treatment (Chemat et al., 2017; Gavahian et al., 2019; Giacometti et al., 2018; Misra et al., 2018).

Juttuporn et al. (2018) conducted an experiment that explored the capability of ultrasound in extracting phenolic compounds from sugarcane bagasse which exploded with steam. The conditions employed in this were 240 W for 6 minutes, due to which the highest yield of 47.65 mg/g was obtained, which consisted of 29.11 mg GAE/g phenolic compounds and 1.47 mg QE/g of flavonoids. Additionally, ABTS radical scavenging assay revealed an antioxidant activity of 82.54 mg TE/g. In another study carried out by Chen et al. (2015), phenolic compounds were extracted from sugar beet molasses using ultrasound treatment. The use of this technology increased the recovered amount to 17.36 mg GAE per 100 mL extract and increased the amount of anthocyanin to 31.81 mg per 100 g extract. Furthermore, an improvement in the antioxidant activity (16.66 mg TE/g) was also observed through the utilization of ultrasound technology. In this study, the solvent used had the following composition (57–63% ethanol and 1.55–1.72 mol/L HCl), and the conditions employed were a temperature in the range of 41–48°C for 66–73 minutes.

*Microwave-assisted extraction.* The utilization of microwave technology for recovering bioactive compounds is an emerging approach (Gavahian et al., 2019; Maric et al., 2018) and is made possible by the occurrence of ionic conduction along with dipole rotation of solvent molecules (influenced by electromagnetic fields), both of which take place simultaneously. In this type of technology, the migration of the solvent molecules is influenced by ionic induction. At the same time, the dipole rotation increases the solvent temperature through the continuous alignment and realignment of the solvent molecules, approximately  $4.9 \times 10^9$  times/s. An important parameter to consider in this technique is the solvent, whose selection largely depends on its capability of dissipating energy to the other molecules (dielectric constant). Due to this, water is generally employed due to the greater dielectric constant (78.3, 20°C) compared to other solvents, specifically methanol and ethanol (32.6 and 24.3 at 20°C, respectively). Additionally, this technique can be performed through three different strategies, the first of which is the utilization of a solvent or a mixture that is highly capable of absorbing microwave energy. Alternatively, a mixture formed from a strong as well as a weak microwave absorbs energy. Another way in which this can be done is by the employment of a solvent that is incapable of absorbing microwave energy, thereby resulting in a high dielectric loss in the matrix (Gavahian et al., 2019).

A study conducted by Fishman et al. (2008) optimized pectin recovery from sugar beet pulp, in which the impact of the conditions used (pressure 25–75 psi, processing time 3–20 min, power 1200 W, frequency 2450 MHz) was evaluated. The study showed that the highest pectin recovery (16.80%) was obtained under the conditions of a pressure of 50 psi for 10 min. Another experiment carried out by Peng et al. (2015) involved the combination of ultrasound and microwave technologies for the purpose of pectin extraction from sugar beet pulp. In this experiment, the authors found that the extracted pectin exhibited a greater average molecular weight, viscosity, emulsifying activity, and stability under the temperature of 92°C for 37 min, compared with that of the conventional method.

*Subcritical fluid extraction.* The utilization of subcritical fluid for extraction involves the combination of pressure and heat to produce subcritical fluids, which are saturated liquids possessing unique properties in terms of the temperature (between atmospheric boiling and critical points) (Gavahian et al., 2019; Zhu et al., 2017). In addition to this, high pressures are especially essential for this system in order to prevent liquid vaporization. Therefore, this system majorly uses water at temperatures between 100–374°C as a solvent, primarily due to the improved characteristics, including the enhanced rate of diffusion, lower viscosity as well as surface tension which allow target compounds to be extracted (Asl & Khajenoori, 2013; Gavahian et al., 2019).

Subcritical fluid extraction was employed in a study performed by Sato et al. (2013) for the recovery of neutral sugars (arabino oligosaccharides and feruloylated arabino-oligosaccharides) and ferulic acid (ester and free forms) from fibers of sugar beet through the flow and batch systems. This study was conducted

within temperatures in the range of 160-180°C for 5-15 minutes for both systems. The highest recovery yields obtained for neutral sugars and ferulic acid were 28.5wt% and 0.55 wt%, respectively, at a temperature of 160°C for 12 minutes using the batch system. Another experiment performed by Chen et al. (2015) employed the combination of ultrasound and subcritical technologies for the recovery of pectin-related materials as well as ferulic acid from sugar beet pulp. Through this, it was found that the highest yield of the pectin-associated compounds obtained was 24.63%, by carrying out the recovery at 10.7 MPa for 30.49 minutes and at a temperature of 120.7°C.

*Enzyme-assisted extraction.* Enzyme-assisted extraction works on the basis of matrix degradation by enzymes for the facilitation of extracting target compounds. For example, the utilization of cellulases, pectinases and other enzymes for the disruption of cell walls can aid in the recovery of phenolic compounds with antioxidant activity (Gavahian et al., 2019; Zhu et al., 2018). This technique is influenced by the properties of the matrix as well as the optimum enzymatic activity, which can be affected by different variables, including pH, temperature, solvent to solid ratio and particle size (Gavahian et al., 2019; Puri et al., 2012; Rosello-Soto, 2016; Vilku et al., 2008).

Zykwinska et al. (2008) conducted an experiment that evaluated the ability of cellulases and proteases for the extraction of pectin from sugar beet pulp at 50°C for 4 hours. This resulted in a pectin extract yield of 4%. Concha-Olmos and Zuniga-Hansen (2012) conducted another experiment that evaluated pectic-oligosaccharides and pectin recovery from sugar beet pulp with the help of two commercial enzymes, namely Rohapect DA6L and Macer8 FJ. The study concluded that Rohapect DA6L was more effective in the recovery of pectic oligosaccharides compared to Macer8 FJ (94.9% of the total pectin).

**Table 5.** Bioethanol Recovery Through Different Distillation Processes

Bioethanol Recovery Technique	Strategy of Technique	Operating conditions	Ethanol wt% yield	Reference
Heat integrated distillation	Different devices are used to decrease the energy consumption and improve the use of the initial energy applied to the distillation system	10% sugarcane bagasse (raw material)	26% increase (from 102.5 to 105.7 L/ton of sugarcane)	(Dias et al., 2009; Dias et al., 2011)
Membrane technology (NaA zeolite membrane)	Recovery of ethanol from aqueous solutions (higher partial pressure of ethanol enables the transport of ethanol to the pores of the membrane from the fermented broth)	NaA zeolite membrane, rice straw (raw material), 100°C, 5-7 bar, 6 L h <sup>-1</sup> (flow rate)	99.5	(Wei et al., 2016)
Membrane-assisted vapor stripping	The presence of a passage of vapor, from water in the fermented broth (which contains ethanol solution), for the volatilization of ethanol (facilitated by a membrane)	Combined system (stripping column + hydrophilic membrane), 5% ethanol solution	80	(Vane et al., 2012)
Feed-splitting	Heating the feed flow by cooling the bottom product flow with the use of a heat exchanger	NR	99.2% (with a 27% reduction in energy use)	(Tavan & Shahhosseini, 2016)



Ohmic-assisted hydro distillation	An ohmic heater in the system produces heat in a volumetric manner, and a condenser gathers and condenses the vapor created.	168 ±5 W, 3L of 75% v/v EtOH-water mixture, 31±1°C (initial temperature), 83°C (final temperature).	84	(Gavahian et al., 2016)
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NR: not reported

**Table 6.** Bioactive Compounds Recovery Through Different ‘Green’ Processes

Bioactive Compound Recovery Technique	Strategy of Technique	Operating conditions	Product	Yield	Reference
Pulsed electric fields	Natural dipole disruption between two molecules which trap bioactive compounds	450 V cm <sup>-1</sup> intensity for 10 min	Sugar-rich extract	79.85%	(Almohammed et al., 2016)
Ultrasound-assisted extraction	Propagation of ultrasound waves in a liquid medium results in a reduction in pressure, forming vapor cavities, which leads to a rise in interactions between the bioactive compound and the solvent	41-48°C for 66-73 minutes, solvent composition (57–63% ethanol and 1.55–1.72 mol/L HCl)	GAE and anthocyanin	17.36 mg/100 mL extract, 31.81 mg/100 mL extract	(Chen et al., 2015)
Microwave-assisted extraction	Dipole rotation of solvent molecules and simultaneous ionic conduction influenced by electromagnetic field	50 psi, 1200 W, 2450 MHz for 10 min	Pectin	16.80%	(Fishman et al., 2008)
Subcritical fluid extraction	Formation of subcritical fluid through the combination of pressure and heat	160°C for 12 min (batch system)	Neutral sugars and ferulic acid	28.5wt% and 0.55wt%	(Sato et al., 2013)
Enzyme-assisted extraction	Enzymatic degradation of matrices to enable compound extraction	Rohapect DA6L and Macer8 FJ commercial enzymes	Pectin and pectic-oligosaccharides	94.9%	(Concha-Olmos & Zuniga-Hansen, 2012)

From Table 5, it is clear that feed splitting is the best type of distillation process that can be carried out for the recovery of bioethanol. This is because, despite leading to an ethanol yield of only 99.2% (compared to 99.5% obtained for membrane technology), feed-splitting puts forward another advantage as it led to a reduction in 27% of the energy used in a study conducted by Tavan and Shahhosseini (2016). In the case of bioactive compounds recovery (Table 6), it is evident that the enzyme-assisted extraction serves as the best technique as it led to the highest product yield of 94.9% in an experiment performed by Concha-Olmos and Zuniga-Hansen (2012), which is much higher than that of the other methods employed.

## CONCLUSION

Various advanced and economical methods are developed to valorize the diverse composition of food waste, from the pre-production stage (FW selection) to the production stage (pretreatment, fermentation and purification). The selection step is essential to sort food waste with high starch and carbohydrate content, which is dominating in cafeteria mixed FW. Conventional acid pretreatment has been considered to be a cheap, high-yielding, and time-efficient method with 31.03 g glucose/L.h generated after the saccharification using commercially available sulfuric acid. On the other hand, in the saccharification and fermentation process, NSSF proves to be the most suitable and efficient method by producing 0.15 g ethanol/g substrate, producing 1.42 g ethanol/L.h, in a time of 38 hours. While the purification step, distillation with feed splitting strategy is reviewed to be the best method as it not only reduced 27% of the energy used but also yielded 99.2% of bioethanol. Lastly, the most preferred technique for the recovery of bioactive compounds was enzyme-assisted extraction, which led to the highest yield of product (94.9%) compared to the other alternatives. Nevertheless, a conclusion of the most appropriate process for the recovery of bioethanol and the bioactive compounds generated along with it is still a challenge merely due to the number of studies and experiments conducted regarding this matter is limited. Therefore, further research concerning "greener" and more "innovative" downstream distillation processes should be conducted along with the processes involved in the extraction of the bioactive compounds to allow a definite conclusion to be made.

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