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REVIEW PAPER

From food industry wastes to second generation bioethanol: a review

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Abstract One-third of food produced for human consumption is lost as waste along the food supply chain. The food industry wastes contain carbohydrates, proteins, lipids, and lignocellulosic substances such as cellulose, hemicellulose, and lignin. These wastes are produced in large quantities worldwide and cause serious environmental problems. Due to the high concentration in organic and nutrient substances, food industry wastes are used for bioethanol production by microorganisms through various fermentation systems. The conversion of a lignocellulosic substance into bioethanol includes three steps: pretreatment, enzymatic hydrolysis, and fermentation. The problems concerning bioethanol production from food industry wastes are related to handling of biomass and application of pretreatment methods in order to improve the conversion of lignocellulosic materials into fermentable sugars. This review provides detailed overview and current knowledge on the pretreatment methods of lignocellulosic substances such as chemical (acid or alkaline, organic solvent), physical (milling, pyrolysis, microwave oven irradiation), physicochemical (steam explosion, hydrothermal processes, ammonia fiber explosion, CO_2 explosion), and biological (fungi, bacteria). Pretreatment is followed by enzymatic hydrolysis with a mixture of suitable enzymes (mainly cellulase, β-glucosidase, pectinase) at 50 °C for 48 or 72 h. The production of bioethanol from food industry wastes is enhanced by enzymatic hydrolysis of the total polysaccharides into metabolizable sugars. The conversion of wastes from the food industry to the second generation ethanol is discussed in details.

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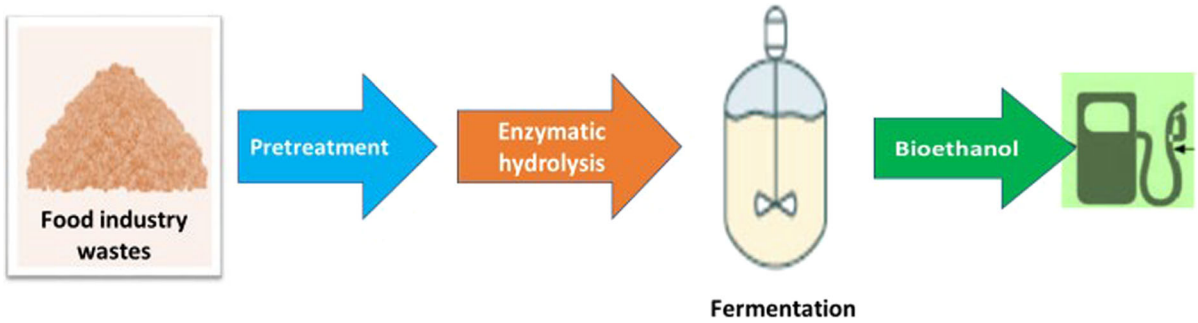
Graphical abstract



Keywords Food industry wastes · Pretreatment · Bioconversion · Fermentation · Bioethanol · Renewable energy

1 Introduction

Petroleum and natural gas are the most important and primary energy sources. However, petroleum causes the emissions of greenhouse gases (GHG) such as CO_2, CO, CH_4, and NO_x (Bayrakci Ozdingis and Kocar 2018). The main global environmental problem is how to reduce the emission of GHG for mitigation of climate change and sustainable growth of economy. This can be achieved by promoting new renewable sources of energy such as geothermal energy, wind energy, solar energy, and biomass based energy (bioethanol, biodiesel, bio-hydrogen) (Singh et al. 2016; Panahi et al. 2020).

In the next years, the increased liquid fuels consumption will lead to the decline of the world fossil fuels reserves. Thus, the development of alternative energy sources is intensively investigated (Roukas and Kotzekidou 2020a; Melikoglu and Turkmen 2019). Bioethanol is the predominant alternative from all available biofuels and constitutes around 74% of all produced biofuels (e Silva et al. 2018). It is an environmentally friendly fuel and contributes to improved air quality, lower GHG emissions and promotes domestic rural economies (Barampouti et al. 2019; Guerrero et al. 2018; Chohan et al. 2020; Parascanu et al. 2021). It has properties similar to gasoline or diesel and could lead to a reduction (70–90%) of GHG emissions. Due to high octane number, bioethanol is a favourable fuel for internal combustion engine to prevent engine knocking and early ignition. The high oxygen content of bioethanol makes the combustion cleaner and results lower emission of toxic substances (Aditiya et al. 2016; Reis et al. 2017; Najafi et al. 2021). Bioethanol can be used in mixtures up to 10% in gasoline without modification of the engines or in higher proportion such as up to 85% in the flexi-fuel vehicles and 100% in special designed engines (Morales et al. 2015).

Taking into account the above advantages of bioethanol, some countries integrated bioethanol into the national fuel system, namely in low blends with gasoline (Guerrero and Munoz 2018). The International Energy Agency recognizes that the promotion of renewable energy will provide an environmentally sustainable future (e Silva et al. 2018). Therefore, the bioethanol production by fermentation has received attention in the last years as it could become a popular alternative for automotive fuel throughout the world (Fang et al. 2019). In 2017, renewable energy supplied about 18.2% of the worldwide energy demand, which has been considered as the largest ever growth of this sector (Solarte-Toro et al. 2019). The production of bioethanol has increased from 13.1 billion gallons in 2007 to 25.7 billion gallons in 2015 (Rastogi and Shrivastava 2017). The world ethanol production should increase about to 158 billion Liter by 2023 (Toor et al. 2020).

Bioethanol is produced mainly from agricultural crops such as corn, sugarcane, and sugar-beet which require large cultivation areas (Roukas and Kotzekidou 2020a). According to the Renewable Fuels Association, worldwide bioethanol production is dominated by the U.S. and Brazil which produce

85% of the world's bioethanol using corn and sugarcane feedstock, respectively. Europe is the third main bioethanol producer using the sugar beet as feedstock (Paixao et al. 2018). The above crops are also used for human food supply. Thus, the production of bioethanol using these crops could increase the food prices. Therefore, cheap substrates could be utilized as alternative to feedstock (Han et al. 2019; Demiray et al. 2019; Sangkharak et al. 2020).

The potential of bioethanol production from biological conversion of waste is huge (Barampouti et al. 2019). Increased agricultural wastes are produced annually by food processing industries causing serious environmental problems (Nikolaou and Kourkoutas 2018). The conversion of food industry wastes to bioethanol requires a multistep process. The main approaches applied include: (a) separate hydrolysis and fermentation (SHF); (b) separate hydrolysis and co-fermentation (SHCF); (c) simultaneous saccharification and fermentation (SSF); (d) simultaneous saccharification and co-fermentation (SSCF); (e) pre-saccharification followed by simultaneous saccharification and fermentation (PSSF) and (f) consolidated bioprocessing (CBP) (Carrillo-Nieves et al. 2019; Tye et al. 2016). The SSF method is more suitable for bioethanol production compared to the conventional SHF process (Chohan et al. 2020).

The fermentation is performed usually by yeasts and some strains of bacteria. *Saccharomyces cerevisiae* is the predominant microorganism used for industrial production of bioethanol. It has some advantages such as high fermentative capacity and ethanol tolerance, low demand on nutrients, and less amounts of byproducts (Roukas and Kotzekidou 2020a). However, this microorganism can only ferment hexose sugars. Various strains of yeasts and bacteria have the ability to ferment pentose sugars (Van Dyk et al. 2013). Among bacteria species, *Zymomonas mobilis* is used mainly for the production of bioethanol; different strains ferment the sugars glucose, fructose, and sucrose while genetically engineered strains ferment arabinose and xylose (Van Dyk et al. 2013; Akbas and Stark 2016). In addition, *Z. mobilis* gives higher ethanol yield and the productivity is about 2.5 times faster than *S. cerevisiae* (Mishra and Ghosh 2019). After the fermentation, the bioethanol is separated from the fermentation broth by distillation or by using more efficient separation technologies such as membrane filtration or molecular sieves (Mojovic et al. 2012). This review will focus on an important issue of food industry, which is the use of the wastes for the production of second generation ethanol.

2 Food industry wastes used for the production of bioethanol

Over recent years, the idea of the converting food processing wastes into high-valued compounds such as bioethanol has increased (Hijosa-Valsero et al. 2019). Food industry wastes are produced in large quantities worldwide and contain soluble sugars, polysaccharides, proteins, lipids, and lignocellulosic compounds such as cellulose, hemicellulose, and lignin (Akbas and Stark 2016; Van Dyk et al. 2013; Hijosa-Valsero et al. 2019). The food industry wastes, which are used for the production of bioethanol are presented in Fig. 1.

Conventional microorganisms are not able to convert the lignocellulosic substances into simple sugars and a pretreatment is necessary to remove the sugars from lignocellulosic materials. In these pretreatments are applied chemical, physical, physicochemical, and biological treatments to modify the structure of lignocellulosic feedstocks (Panahi et al. 2020; Hijosa-Valsero et al. 2019; Stamenkovic et al. 2020; Niphadkar et al. 2018; Di Donato et al. 2019). The chemical pretreatments include acid or alkali at high temperatures, organic solvent, and enzymatic hydrolysis (Panahi et al. 2020; Hijosa-Valsero et al. 2019; Stamenkovic et al. 2020; Niphadkar et al. 2018; Di Donato et al. 2019; Gil and Maupoey 2018; Demiray et al. 2018; Farias and Filho 2019; Brar et al. 2019; Zhou et al. 2019; Pinheiro et al. 2019). In acid process, the lignocellulosic substances are commonly treated with HCl, H_2SO_4, HNO_3, H_3PO_4, or peracetic acid at 130–210 °C for different times. The alkaline pretreatment causes the degradation of lignin (Panahi et al. 2020).

The physical pretreatments involve mechanical sized reduction (milling, grinding, chipping), pyrolysis, and microwave oven irradiation (Panahi et al. 2020; Hijosa-Valsero et al. 2019; Gil and Maupoey 2018). Pyrolysis is carried out at high temperatures (> 300 °C). In this stage, cellulose is degraded mainly into glucose, which is used for the production of bioethanol by microorganisms (Panahi et al. 2020).

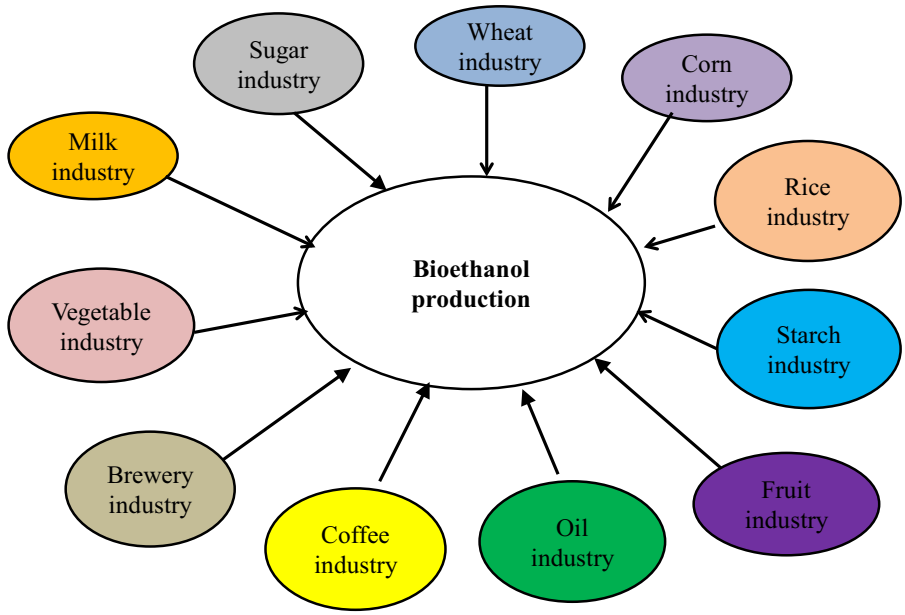


Fig. 1 Food industry wastes used for the production of second generation ethanol

The physicochemical pretreatment includes steam explosion or autohydrolysis, hydrothermal processes, ammonia fiber explosion (AFEX), and CO_2 explosion (Panahi et al. 2020; Hijosa-Valsero et al. 2019). Steam explosion or autohydrolysis is carried out at high temperature (160–290 °C) and high pressure steam (2–5 MPa) for a few minutes. The scope of this method is the recovery of xylose up to 65%. In hydrothermal process, the lignocellulosic wastes are treated at 170–230 °C and 5 MPa for 20 min. Using this method, sugar oligomers are released from the lignocellulosic materials of the agricultural wastes. AFEX method uses liquid NH_3 and steam explosion at pressure > 1.21 MPa for 5–30 min (Panahi et al. 2020). Biological pretreatments used mainly fungi, bacteria or mixture of them for delignification of food industry wastes through the action of enzymes which are produced by microorganisms.

The food industry waste valorization for bioethanol production has some advantages and disadvantages concerning the pretreatment method, the chemical compounds addition, and the application of fermentation system. The chemical treatment is used for the conversion of hemicellulose into soluble sugars and increase the degree of hydrolysis of cellulose to glucose during the enzymatic hydrolysis. The disadvantage of the above pretreatment is the formation of some substances (usually 5-hydroxymethylfurfural) which inhibit the growth of the microorganism applied for the production of bioethanol. Therefore, some detoxification methods such as extraction, evaporation, adsorption, and neutralization are used to remove the inhibitors before fermentation (Hijosa-Valsero et al. 2019).

The mechanical pretreatment reduces the crystallinity of cellulose of the solid wastes improving the further processing such as enzymatic hydrolysis. The microwave irradiation increases significantly the internal heat within the inhomogeneous material. It enhances the disruption of structure of the lignocellulosic waste improving the hydrolysis of cellulose to simple sugars (Panahi et al. 2020). This method appears some advantages such as it is simple and does not use high temperatures, high pressures, and chemical additives. On the other hand, it appears slow hydrolysis rate, low yield, and high cost. The above disadvantages limit its commercial application (Panahi et al. 2020). The advantages of the physicochemical pretreatment are the lignin transformation, the hemicellulose solubilization, and the low formation of inhibitors; but, the method has some disadvantages such as high energy consumption, generation of toxic compounds, very high pressure requirements, and is still not used at commercial scale. Whereas,

applying the biological pretreatment the lignin and hemicellulose degradation is achieved by low energy consumption, low capital cost, and no need of chemicals addition, but a low rate of substrate hydrolysis is achieved (Carrillo-Nieves et al. 2019).

Overall, the pretreatment method of food wastes for bioethanol production is still costly (making up more than 40% of the production cost). Therefore, an efficient conversion of total available sugars in lignocellulosic raw material is required to improve the economic feasibility of biomass to bioethanol process (Panahi et al. 2020). The chemical compounds which are used during the pretreatment of food wastes improve the following step of enzymatic hydrolysis; but, they increase the cost of the final product. The fermentation system applied for bioethanol production from food processing waste depends on the type of the substrate. In case of a liquid substrate, the extraction of the sugars is expensive. On the other hand, solid substrate can be directly used by solid-state fermentation without the previous extraction of sugars from the substrate. Thus, low consumption of energy is needed.

For the valorization of each food waste, the key factors should be paid attention are the pretreatment method, the microorganisms and the fermentation system. The pretreatment of the substrate should be easy in application, inexpensive, and a large amount of lignocellulosic material are converted to simple sugars. The microorganisms should have the ability to produce high bioethanol concentration. In order to achieve high bioethanol yield the fermentation conditions such as initial sugar concentration, pH, temperature, and agitation speed should be optimized. The most important stages, which are used for the production of bioethanol from food industry wastes are presented in Fig. 2. The food processing wastes can be utilized as animal feed, soil fertilizer, and the production of pectin, dietary fibers, phenolic compounds, lycopene, grape seed oil, vanillin, enzymes, and xylitol (Van Dyk et al. 2013). In this section, we will describe in details the food industry wastes, which can be used for the production of bioethanol by microorganisms.

2.1 Sugar industry wastes

2.1.1 Molasses

Cane and beet molasses are by-products of the sugar industry and they are used for animal feed, baker's yeast production, and pharmaceuticals (Amid et al. 2021; Akbas and Stark 2016). Molasses is a low cost substrate and it can be used for fermentation without any treatment because the microorganisms convert directly the sugar content (sucrose, glucose, fructose) into bioethanol (Roukas and Kotzekidou 2020a; Hijosa-Valsero et al 2019; Jayus et al. 2016; Khatiwada et al. 2016; Rathnayake et al. 2018).

Jayus et al. (2016) and Muruaga et al. (2016) used as substrates sugar cane molasses and sugar cane molasses supplemented with 10% cane juice for bioethanol production and found a maximum bioethanol concentration of 121.0 and 120.0 g/L using the commercial baker's yeast and *S. cerevisiae* A_2 strain isolated from sugar cane molasses, respectively. In another work, blackstrap molasses was used for bioethanol production by immobilized cells of *S. cerevisiae* on thin-shell silk cocoons and a high bioethanol concentration of 98.6 g/L was obtained (Rattanapan et al. 2011). In this study, the immobilized yeast cells retained the ability to produce bioethanol for 10 days. The above authors studied the production of bioethanol in continuous culture in a packed-bed reactor at a dilution rate of 0.36 h^{-1} and found a maximum ethanol concentration of 52.8 g/L and an ethanol productivity of 19.0 g/L/h.

Tang et al. (2010) reported the utilization of non-sterilized molasses for bioethanol production by a flocculating yeast strain KF-7 in continuous culture. They found that the system produced bioethanol for more than 30 days with a bioethanol concentration of 80.0 g/L and a high ethanol productivity of 6.6 g/L/h. Sowatad and Todhanakasem (2020) used sterilized molasses for bioethanol production and found that *S. cerevisiae cells* immobilized on sugarcane bagasse produced 97.0 g/L bioethanol for 10 days. Roukas and Kotzekidou (2020a) developed a rotary biofilm reactor (RBR) for long-term bioethanol production from non-sterilized beet molasses by *S. cerevisiae* in repeated-batch fermentation. In this study, the RBR was operated continuously for 60 days with a stable bioethanol concentration of 52.3 g/L.

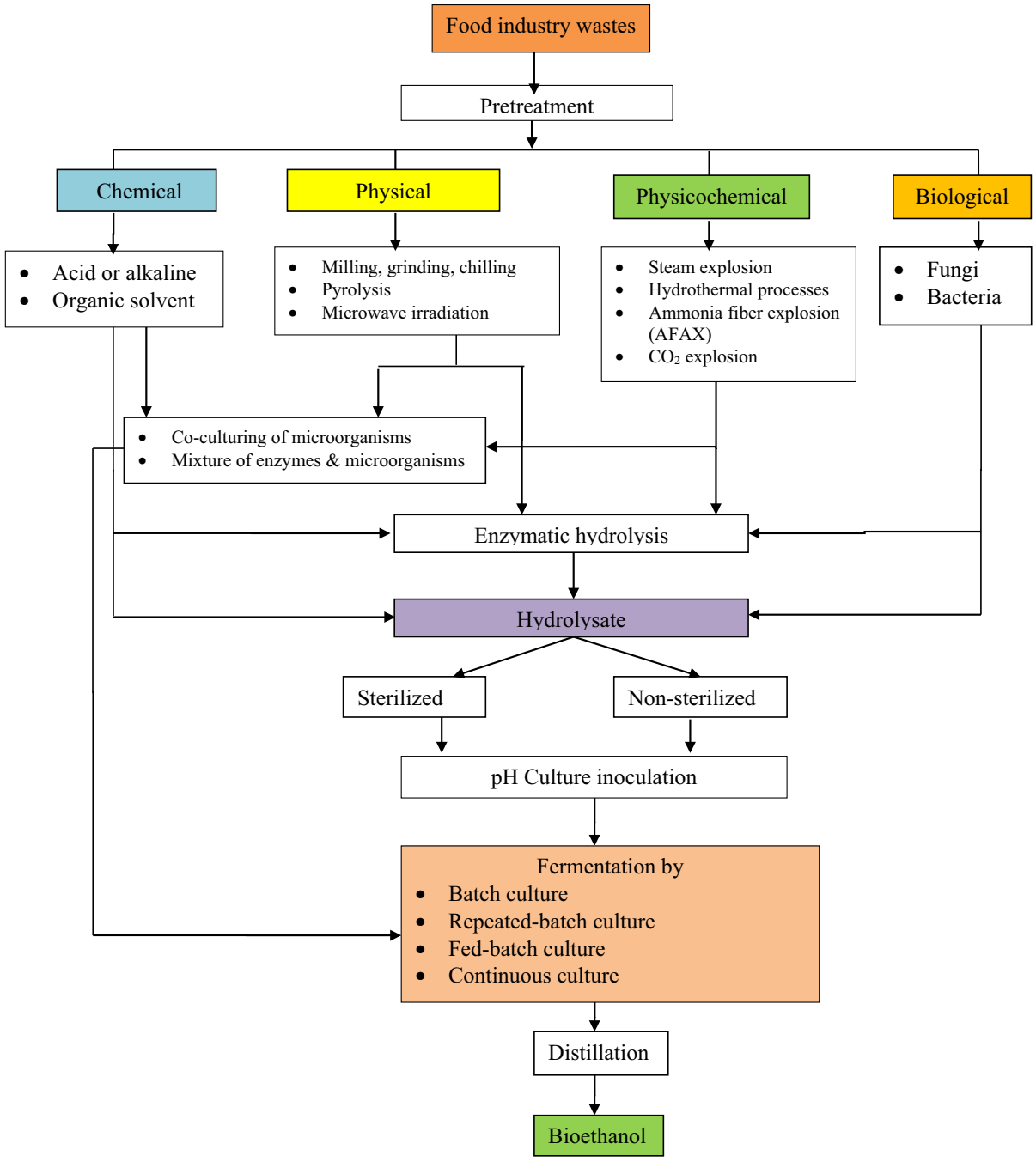


Fig. 2 Pretreatment methods and enzymatic hydrolysis of food industry wastes used for bioethanol production

2.1.2 Sugarcane bagasse

Sugarcane bagasse is the main waste of the sugar industry, which is obtained from sugarcane after juice extraction at a ratio of 240–275 kg of bagasse with 50% humidity per ton of sugarcane (Eblaghi et al. 2016; Saha et al. 2019; da Siva Martins et al. 2021). The annual production of sugarcane waste is about 279 million tons (Jugwanth et al. 2020). It is consisted of cellulose (40–45%), hemicellulose (30–35%), lignin

(20–30%), protein (3%), silica (2%), ash (1.9–2.4%), and other elements (1.7%) (Bhattacharyya et al. 2012; Sarkar et al. 2012).

The main stages involved in sugarcane bagasse bioethanol production are: bagasse pretreatment, hydrolysis of pretreated lignocellulose biomass to monosaccharides, and fermentation of these sugars to bioethanol (Saha et al. 2019). There are several methods used for the pretreatment of sugarcane bagasse. These include microwave-alkali, organic and inorganic acids, ionic liquids, steam explosion with alkaline delignification, organosolv process with dilute acid, sono-assisted acidic pretreatments, ultrasound-assisted treatment in cellulase aqueous-N-methylmorpholine N-oxide, imidazole, and a highly oxidative solution hypochlorite-hydrogen peroxide (Ox-B) (Eblaghi et al. 2016; Saha et al. 2019; Jugwanth et al. 2020; Santosh et al. 2017; Valladares-Diestra et al. 2021; da Siva Martins et al. 2021). The hydrolysis is carried out enzymatically or with the effect of acids at high temperature conditions. The fermentation of the cellulose and hemicellulose hydrolysates is carried out by specific microorganisms in order to produce bioethanol.

Xie et al. (2014) used sugarcane bagasse for bioethanol production. The substrate was treated with mild alkali followed by enzymatic hydrolysis and fermentation. In this case, a high bioethanol concentration (39.8 g/L) was obtained after 96 h of incubation. Another substrate used for bioethanol production was sugarcane bagasse hydrolysate blended with molasses (Gutierrez-Rivera et al. 2015). The substrate was inoculated with *S. cerevisiae* ITV-01 and *Scheffersomyces stipitis* NRRL Y-7124. The highest bioethanol concentration was 53.8 g/L. In another interesting work, sugarcane bagasse pretreated with microwave alkali followed by enzymatic hydrolysis with cellulase, endoglucanase, β-glucosidase, and xylanase (Singh et al. 2013). The maximum bioethanol concentration was 15.4, 11.8, and 9.4 g/L when *S. cerevisiae* cells immobilized on sugarcane bagasse, Ca-alginate, and agar beads, respectively.

Silva et al. (2016) evaluated the use of cell recycle of *S. cerevisiae* to produce bioethanol from sugarcane bagasse hydrolysate in repeated-batch fermentation. The feedstock was treated with diluted phosphoric acid followed by alkaline delignification and enzymatic hydrolysis. The free cells of the yeast retained their activity to produce bioethanol (50.0 g/L) for 5 recycles. Saha et al. (2019) used sugarcane bagasse hydrolysate for bioethanol production by *S. cerevisiae* in continuous culture using a membrane integrated hybrid reactor. A maximum bioethanol concentration (43.2 g/L) was obtained after 19 h. Lin et al. (2013) developed a rotary drum reactor to produce bioethanol from sugarcane bagasse by a thermotolerant strain of *Kluyveromyces marxianus* and commercial cellulase using SSF process. They found a maximum bioethanol concentration of 24.6 g/L with a theoretical ethanol yield of 79%.

Hama et al. (2018) developed a technology of recycling *S. cerevisiae* cells to produce bioethanol from sugarcane bagasse supplemented with molasses. The results showed that a maximum bioethanol concentration of 63.5–67.7 g/L was obtained in six repeated-batch fermentations. Valladares-Diestra et al. (2021) produced bioethanol from sugarcane bagasse after pretreatment with imidazole at 160 °C for 1 h followed by enzymatic hydrolysis with cellulase and xylanase. The results showed a maximum bioethanol production of 218 L/ton of sugarcane bagasse. Recently, da Siva Martins et al. (2021) used sugarcane bagasse for bioethanol production after pretreatment with Ox-B and enzymatic hydrolysis with cellulase and β-glucosidase. They found a high bioethanol yield of 70%. A schematic presentation of bioethanol production from sugar industry wastes is shown in Fig. 3.

2.2 Wheat industry wastes

2.2.1 Wheat bran wastes

Wheat bran is an abundant and low-cost material for the production of bioethanol due to its low pretreatment cost. It is consisted of (% of the dry matter) starch 11.0, cellulose 10.7, hemicellulose 39.0, lignin 5.0, protein 18.0, and ash 0.05 (Cripwell et al. 2015). The production of bioethanol from wheat bran waste has been studied by Cripwell et al. (2015). They used two recombinant *S. cerevisiae* strains or a recombinant cellulase cocktail (RCC) with the above strains in a SSF process at 30 °C for 60 h. The results showed that the strains of the yeast produced similar amounts of bioethanol (5.3–5.0 g/L). When the fermentation was carried out in SSF process using the recombinant yeasts with the RCC the bioethanol concentration increased to 7.0 g/L. Generally, the study

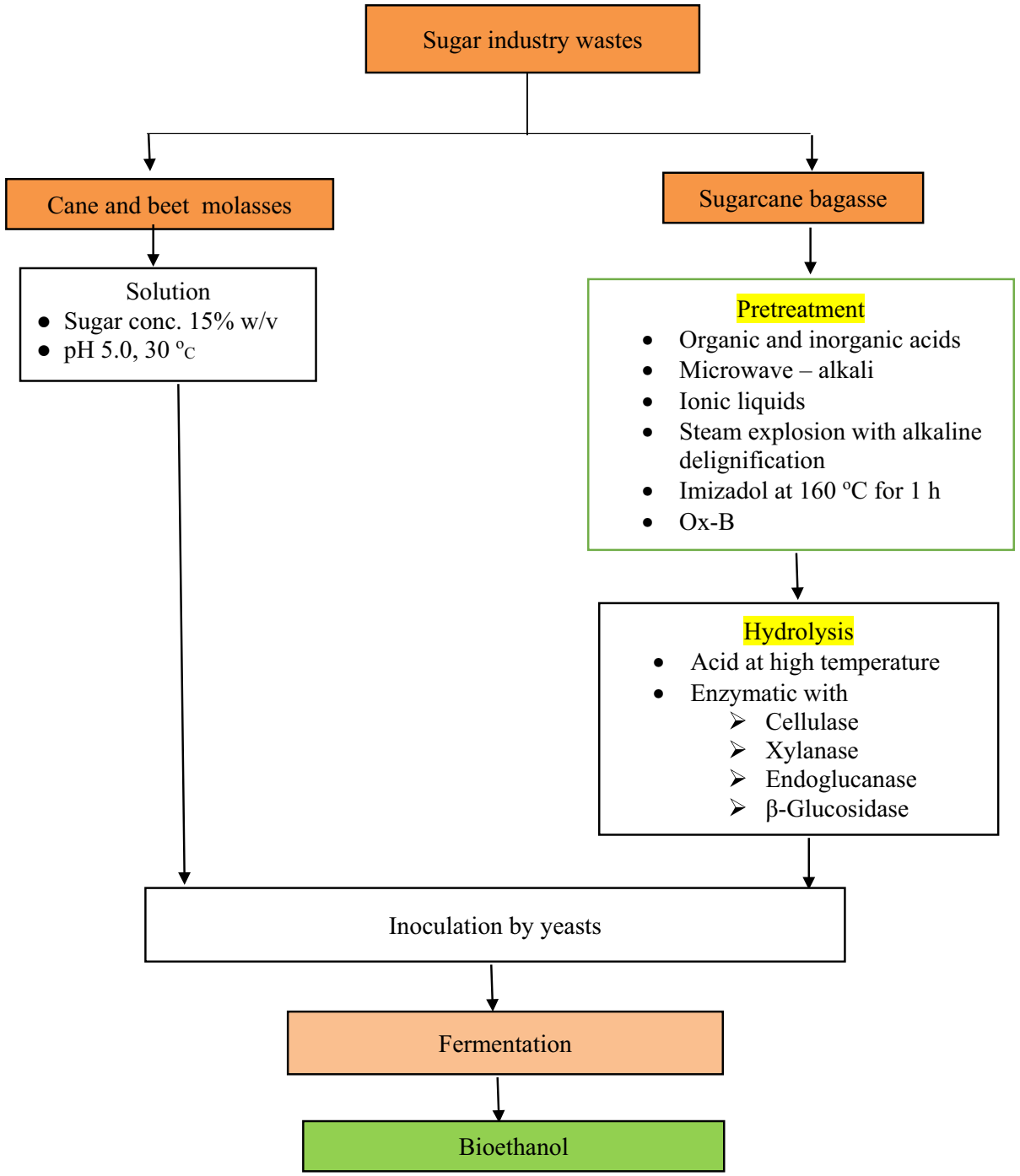


Fig. 3 Schematic presentation for bioethanol production from food industry wastes using different pretreatment methods and acid or enzymatic hydrolysis

demonstrates that the recombinant yeast strains can efficiently convert the starch of the wheat bran to bioethanol while the addition of RCC into the medium improved the production of bioethanol.

2.2.2 Bakery waste

Wheat bread is the common food in many countries. When it is not used for the primary purpose, it is discharged from the bakery store as waste which causes a serious environmental problem (Han et al. 2019; Mihajlovski et al. 2020). Bread waste contains 50–60% carbohydrate which is the major component of the waste. It can be hydrolyzed into simple sugars which can be utilized for bioethanol production by microorganisms (Han et al. 2019; Adetya et al. 2017). Han et al. (2019) used bakery waste to produce bioethanol. The hydrolysis of bakery waste was performed in a bioreactor with working volume of 0.5 L using α-amylase at 95 °C and agitation speed of 200 rpm. The obtained bread waste hydrolysate was inoculated with the yeast *S. cerevisiae* and the fermentation was carried out at 30 °C. The highest bioethanol production (46.6 g/L) was achieved after 40 h. This value is higher than that using the glucose as feedstock since the bread waste hydrolysate provides both the carbon and nitrogen sources for the production of bioethanol (Han et al. 2019). Mihajlovski et al. (2020) studied the enzymatic hydrolysis of bread waste by a newly isolated *Hymenobacter* sp. CKS3 strain. The waste bread hydrolysate containing 20 g/L reducing sugars was fermented by *S. cerevisiae* at 30 °C for 24 h. The maximum bioethanol concentration was 17.3 g/L.

2.3 Corn industry wastes

In the corn industry, the most significant waste is the corncob residue (CCR). Corncob is the core of the corn on which grows the kernel. CCR is the corncob after removing the kernel during the processing of the corn. It consists of high amount of hemicellulose which is extracted by dilute-acid pretreatment for xylose and xylitol production. The remaining residue is a potential feedstock for bioethanol production due to its high cellulose content (Fan et al. 2013). Before fermentation, the CCR is treated with alkali or sulfite to remove the lignin fraction. During this phase, some compounds such as furfural, 5-hydroxymethyl furfural, and acetic acid are formed which have inhibitory effects on microorganisms used for the production of bioethanol. For this reason, detoxification of the substrate is necessary for optimal fermentation of CCR hydrolysate.

Fan et al. (2013) used a yeast strain of *Pichia guilliermondii* to produce bioethanol from CCR hydrolysate in repeated batch and repeated fed-batch fermentation. Enzymatic hydrolysis was performed with cellulase at 50 °C for 72 h. The results showed an average bioethanol concentration of 36.0 and 51.0 g/L in five repeated-batch fermentations and three repeated fed-batch fermentations, respectively. In another study, corncob used for bioethanol production by *K. marxianus* using SHF and SSF process (Zhang et al. 2010). Acid hydrolysis was carried out with 0.5% H_2SO_4 at 121 °C for 2 h. Enzymatic hydrolysis was performed with commercial cellulase at 50 °C for 48 h. Hydrolysates obtained after acid and enzymatic pretreatments were used for the production of bioethanol by *K. marxianus* at 37 °C for 48 h in static culture. Among the two fermentation systems, SSF gave the highest bioethanol production (5.7 g/L). Garcia-Torreiro et al. (2016) reported a bioethanol concentration of 11.5 g/L when the yeast *Pachysolen tannophilus* was grown in CCR hydrolysate using SSF process. In this case, the CCR was pretreated with the basidiomycete *Irpex lacteus* for the reduction in lignin content. The hydrolysis was carried out with a cocktail of enzymes consisted of cellulase, beta-glucosidase, xylanase, and beta-xylosidase at 50 °C for 24 h.

2.4 Rice industry wastes

2.4.1 Rice waste biomass

Rice waste biomass (RWB) is a cheap lignocellulosic material which can be used for the production of bioethanol. Before fermentation, RWB was pretreated with chemical methods for the conversion of lignicellulosic materials to simple sugars (Saratale and Oh 2015). Alkaline pretreatment at high temperature followed by enzymatic hydrolysis resulted in a yield of 0.5 g reducing sugar/g of RWB with a hydrolysis degree of 69.2%. Alkaline pretreatment of RWB followed by treatment with sodium chloride and sodium bicarbonate and a lower dose of enzyme gave a yield of 0.7 g reducing sugars /g of RWB with a hydrolysis yield of 90.6%. The maximum bioethanol yield and sugar consumption from the above hydrolysate were 0.465 g/g and 95%, respectively. In addition, the significant delignification of the RWB with the above developed pretreatment and the

production of bioethanol without detoxification of the substrate demonstrate the feasibility of the process.

2.4.2 Deoiled rice bran

Deoiled rice bran (DORB) is a renewable and cheap agro-industrial waste suitable for the production of bioethanol. Agrawal et al. (2019) utilized DORB hydrolysate for bioethanol production by *S. cerevisiae* MTCC 4780 under optimized fermentation conditions. The fermentation was carried out at 30 °C and the highest bioethanol concentration was 9.68% (v/v) after 48 h of incubation.

2.4.3 Rice hull

Rice hull or rice husk is the hard protecting covering of rice grain which is separated from the grain during milling process. Asia,is the largest rice producer in the world producing about 90.6%of the annual *global production*. In a milling process, 1000 kg of rice paddy produces 200 kg of hull which contains a mixture of pentose and hexose (Taghizadeh-Alisaraei et al. 2019a, b). Rice hull produces approximately 0.45 g of sugars / g of dry hull. It consists of glucan 30%, xylan 13.5%, lignin 22.5%, ash 21%, and others 13% (Ebrahimi et al. 2017). The conversion of rice hull to bioethanol includes three steps: pretreatment for the removal of lignin and the decrease of cellulose polymerization and crystallinity, hydrolysis for the release of the sugars, and fermentation of sugars to bioethanol by microorganisms such as yeasts, bacteria or fungi (Ebrahimi et al. 2017).

Pretreatment is one of the most expensive steps in bioethanol production. In order to overcome this problem, Ebrahimi et al. (2017) investigated a new pretreatment method of rice hull using acidified aqueous glycerol and glycerol carbonate at 130 and 90 °C respectively, for 60 min. The hydrolysis was performed with the enzyme cellulase for 72 h. The SSF process was conducted anaerobically at 37 °C by the yeast *S. cerevisiae* using 5% (w/v) glucan and cellulase at a ratio of 10 FPU/g glucan. The maximum bioethanol production was 8.8 and 11.6 g/L after 3 days of fermentation using pretreatment rice hull with acidified aqueous glycerol and glycerol carbonate, respectively. A mixture of rice hull and orange peel wastes was utilized for bioethanol production by Taghizadeh-Alisaraei et al. (2019a). The pretreatment and the hydrolysis of the substrate was carried out with sulfuric acid 3% at 120 °C for 60 min. Hydrolyzed matter consists of glucose and arabinose. The substrate was inoculated with the yeast *S. cerevisiae* at a ratio of 5 g yeast /kg of dry matter. The fermentation was performed at 30 °C for 32 h and the highest bioethanol concentration was 22.8 g/L.

2.5 Starch industry wastes

2.5.1 Potato wastes

Potatoes are mostly used for human consumption but they can be also processed into a variety of products such as starch, chips and crisps, fries, mashed potatoes, and dehydrated products (Khawla et al. 2014; Atitallah et al. 2019). During processing, approximately 15–50% of the potatoes depending on the procedure applied are generated as wastes such as peels, potato pulp, waste potato mash, and potato processing water. The above wastes cause environmental problems due to spoilage by microorganisms (Khawla et al. 2014; Atitallah et al. 2019; Hossain et al. 2018; Izmirlioglu and Demirci 2017). Usually, potatoes are peeled during processing. The potato peel waste (PPW) is a "zero value" waste which contains significant amount of starch, cellulose, hemicellulose, and lignin (Sheikh et al. 2016; Galhano dos Santos et al. 2016; Richelle et al. 2015). The production of bioethanol from PPW includes three steps: liquefaction, saccharification, and fermentation. Liquefaction is carried out with a mixture of amylases which causes hydrolysis of starch to maltodextrins and maltose at 95 °C while glucoamylase is used for saccharification step to produce glucose at 60 °C (Atitallah et al. 2019; Izmirlioglu and Demirci 2017).

Izmirlioglu and Demirci (2016, 2017) used potato waste (PW) and potato waste hydrolysate (PWH) for production of bioethanol in biofilm reactors by co-culture of *Aspergillus niger* and *S. cerevisiae* and free cells of *S. cerevisiae,* respectively. The hydrolysis of PW was carried out with α-amylase at 95 °C for 3 h and amyloglucosidase at 60 °C for 72 h. Under the above conditions, PW and PWH gave a maximum bioethanol concentration of 37.9 and 37.0 g/L, respectively. Khawla et al. (2014) and Hossain et al. (2018) used PPW as feedstock for bioethanol production treated with commercial enzymes (amylase and amyloglucosidase) or by consolidated bioprocessing

(liquification, saccharification, and fermentation in a solo-step process) and found a maximum bioethanol concentration of 21.0 and 21.7 g/L, respectively. In another studies (Chintagunta et al. 2016; Subhash et al. 2016; Pinaki and Lhakpa 2016) reported the production of bioethanol from PW by *A. niger* and *S. cerevisiae* for saccharification and fermentation process resulting in a maximum bioethanol concentration of 48.7, 41.8 and 125.0 g/L, respectively. Maroufpour et al. (2019) utilized PPW for bioethanol production by *Z. mobilis* and found a maximum bioethanol production of 5.2 g/L after conversion of starch to glucose with acid hydrolysis.

Another substrate used for the production of bioethanol is the sweet potato residues (SPR_s) which is the residue after the extraction of starch from sweet potatoes (Wang et al. 2016). Sweet potato contains starch, glucose, fructose, sucrose, and cellulose (Wang et al. 2016; Dewan et al. 2013). SPRs used as substrate for bioethanol production after hydrolysis by a mixture of cellulase and pectinase (Wang et al. 2016). The hydrolysate was fermented by the yeast *S. cerevisiae* to produce 79.0 g/L bioethanol.

2.5.2 *Cassava wastes*

Cassava is one of the most consumed agricultural products. It contains starch, cellulose, hemicellulose, lignin, protein, fat, and other minor components (Trakulvichean et al. 2019; Aruwajoye et al. 2020). Cassava roots are mainly processed for the production of starch, chips, pellets, and bioethanol (Trakulvichean et al. 2019). During the processing large quantities of wastes such as cassava pulp, cassava peels and cassava wastewater are generated which cause significant environmental pollution (Bolade et al. 2019). The bioethanol production from cassava wastes is very complex and involves pretreatment, hydrolysis, and fermentation. The pretreatment of biomass improves enzymatic hydrolysis facilitating the access of cellulase on the cellulose structure (Nanssou et al. 2016).

Icalina et al. (2018) investigated the bioethanol production from cassava waste pulp (CWP) and found a maximum production of 4.7 g/kg of fresh CWP after 7 days of fermentation. A high bioethanol concentration of 28.2 g/L was obtained from cassava peel waste (CPW) hydrolyzed with 0.5 M sulfuric acid at 100 °C for 60 min after 4 days of incubation (Abidin et al. 2014). Aruwajoye et al. (2020) reported a maximum bioethanol production of 0.58 g/g sugar consumed when CPW was soaked in HCL solution at 69.68 °C for 2.57 h and then was sterilized at 121 °C for 5 min. Nanssou et al. (2016) used cassava stems and peelings for bioethanol production after pretreatment by thermohydrolysis at 210 °C for 45 min and the pretreatment residue was hydrolyzed with cellulase. In this case, the bioethanol concentration was 5.3 g/100 g cassava stems and 2.6 g/100 g cassava peelings.

2.5.3 *Sorghum wastes*

Sorghum belongs to the grass family *Poaceae* and is the fifth most important cereal worldwide (El-Imam et al. 2019; Nasidi et al. 2016). During starch removal from the sorghum, waste bran is produced which can be used for bioethanol production. The traditional processing method of sorghum involves steeping, wet-milling and sieving (El-Imam et al. 2019). The bran which is removed during this process is usually discarded or fed to animals as a low-value feed.

Sorghum bran used for bioethanol production by El-Imam et al. (2019) after acid and enzymatic hydrolysis to produce fermentable sugars. The acid hydrolysis of white bran or red bran was carried out with sulfuric or nitric acid (1% or 3% w/w) at 121 °C for 15 or 30 min, respectively while the enzymatic hydrolysis was carried out using amylase and amyloglucosidase. The hydrolysate was fermented by the yeast *K. marxianus* to produce 24.3 g/L bioethanol. Pandebesie et al. (2019) used sorghum stalks waste to produce bioethanol. It was pretreated with 0.25% sulfuric acid at 121 °C for 10 min. The enzymatic hydrolysis was performed using a mixture of the strains *Trichoderma viride* and *A. niger* at a ratio of 2:1. After hydrolysis, the substrate utilized for production of bioethanol using the consortium of *S. cerevisiae* CC 3012 and *Pichia stipitis*. The bioethanol concentration was 36.1 g/L after 24 h of fermentation.

2.5.4 *Sago pitch wastes*

The sago pitch waste (SPW) is the residue after the extraction of starch from pitch of *Metroxylon sagu* (sago palm) (Thangavelu et al. 2014, 2019). It contains up to 58% starch, 23% cellulose, 9.2% hemicellulose, and 4% lignin (w/w of dry weight) (Thangavelu et al. 2014). Thangavelu et al. (2014, 2019) investigated the

bioethanol production from SPW using microwave treatment. It is a potentially faster method for thermal treatment of SPW with low pressure and temperature. In addition, this method includes rapid and efficient heating in a controlled environment, increasing processing rates and substantially shortening reaction times by up to 80%. The above authors reported a maximum bioethanol yield of 15.6 and 31.0 g ethanol/100 g dry SPW using microwave hydrothermal hydrolysis accelerated by carbon dioxide and microwave assisted acid hydrolysis, respectively.

2.5.5 *Triticale bran*

Triticale is a hybrid of rye and wheat. It has a number of potential advantages for bioethanol production due to its ability to adapt to stresses and thrive on marginal soils with a lower nitrogen requirement during crop growth. Triticale bran (TB) is the residue after removal of starch from the grain. It can account up to 19% of the grain. The bran contains residual starch, cellulose, and hemicellulose (Garcia-Aparicio et al. 2011). TB is designated as starch-free triticale bran (SFTB) using degrading enzymes of starch. The SFTB is pretreated with 0.1% of sulfuric acid at 160 °C for 22.5 min and then it is hydrolyzed using a mixture of the enzymes Spezyme CP and Novozyme 188 at 50 °C and pH 4.8. Under these conditions, the SFTB used as substrate for bioethanol production and obtained 193.4 g of ethanol/ton dry SFTB (Garcia-Aparicio et al. 2011). The most important stages used for bioethanol production from starch industry wastes are shown in Fig. 4.

2.6 Fruit industry wastes

2.6.1 *Citrus wastes*

Citrus fruits (oranges, mandarins, lemons, sweet limes, and grapefruits) are the most abundant crops in the world (Choi et al. 2015a, b). The production of citrus fruits generates large quantities of waste. This is mainly due to rejects when packing fresh fruit and the wastes generated by processing industries (Fito et al. 2015). The annual production of citrus fruits is more than 115 million tons and about 30 million tons of the fruits are used for juice production. The residual from the juice industries is almost 50% of the wet fruit biomass (Choi et al. 2015a, b; John et al. 2017).

Citrus peel waste (CPW) is the main residue of the citrus processing industries contributing 10 million tons of waste per year worldwide in 2016 (Zema et al. 2018; Jeong et al. 2021). It contains soluble sugars such as glucose, fructose, and sucrose, pectin, cellulose, hemicellulose, D-limonene, and essential oils (Choi et al. 2015a, b; John et al. 2017; Zema et al. 2018). Some of these compounds (D-limonene, essential oils) cause toxic effects on the microbial community and the efficient removal of these compounds from CPW requires a pretreatment step (Choi et al. 2015a, b; Fazzino et al. 2021). In addition, a pretreatment method is necessary to convert cellulose, hemicellulose, and pectin to fermentable sugars. The pretreatment methods include mechanical comminution, dilute acid hydrolysis, hydrothermal sterilization or autohydrolysis, popping, and steam explosion. The enzymatic hydrolysis is carried out using cocktails of cellulase, β-glucosidase, and pectinase (John et al. 2017).

Sukamoto et al. (2013) and Kyriakou et al. (2019) used orange processing waste (OPW) and orange peel hydrolysate for production of bioethanol and reported a maximum bioethanol concentration of 21.0 g/100 g dry OPW and 72.0 g/L, respectively. Mandarin peel waste (MPW) pretreated with drying, steam explosion, and popping pretreatment used as feed stock for bioethanol production and found a maximum bioethanol production of 0.34 g/g waste, 43.4 kg/ton raw MPW, and 0.47 g /g sugar consumed, respectively (Kiran et al. 2014; Boluda-Aguilar et al. 2010; Choi et al. 2013).

2.6.2 *Apple and grape pomace*

Apple pomace is a waste of the food industry consisted of peel, seeds, and solid parts which are generated after juice extraction (Evcan and Tari 2015; Pathania et al. 2017). It consists of 25–35% of the weight of the fruit and causes important environmental problems. Million metric tons of *apple pomace* are estimated to be *generated worldwide* every *year* (Evcan and Tari 2015). It contains carbohydrates, cellulose, hemicellulose, lignin, and minerals (Evcan and Tari 2015; Pathania et al. 2017). Prior to ethanol fermentation, it needs to be pretreated in order to release fermentable sugars.

Evcan and Tari (2015) utilized apple pomace hydrolysate to produce bioethanol by a co-culture of

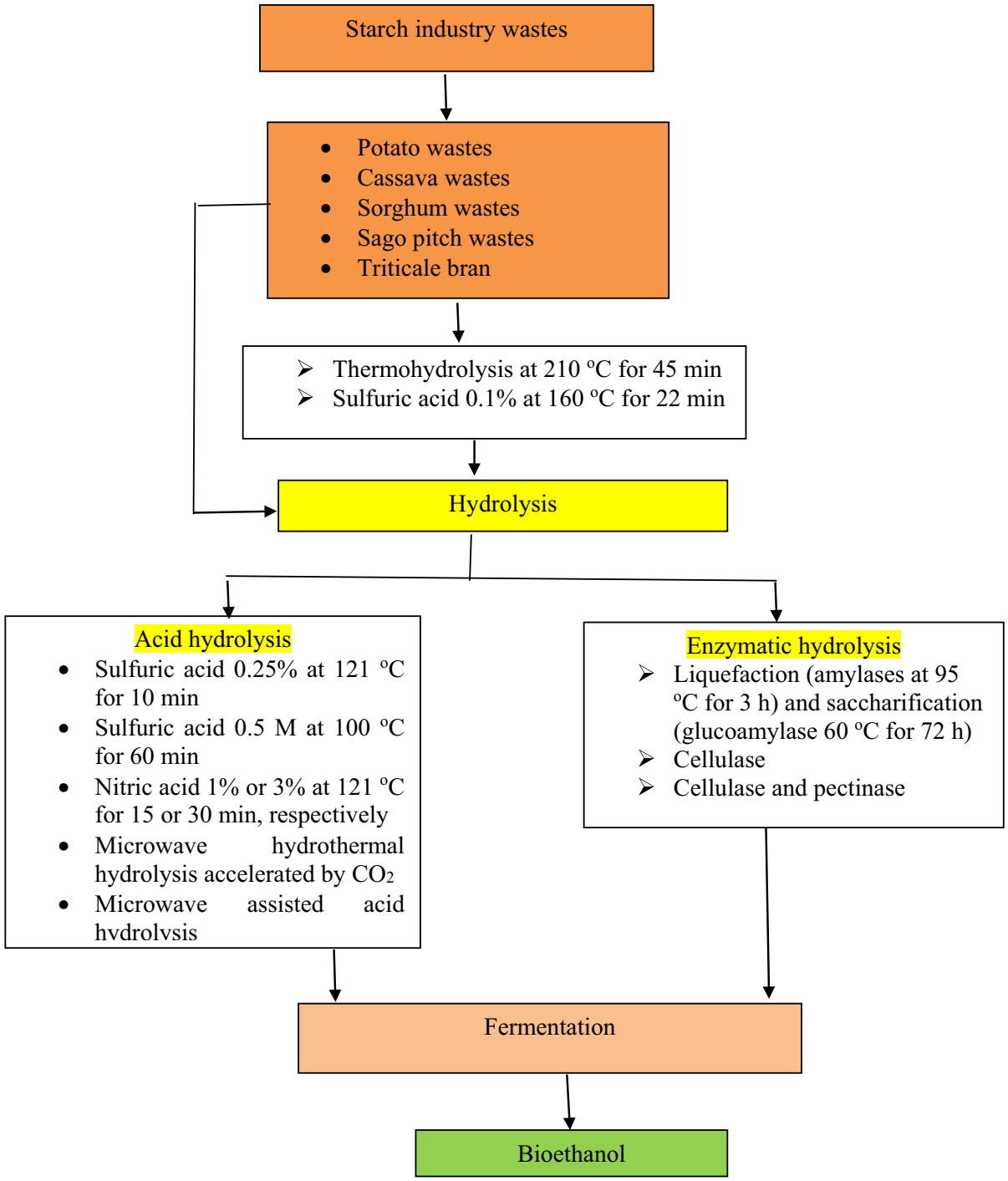


Fig. 4 A flow diagram for bioethanol production from starch industry wastes using physicochemical pretreatment and acid or enzymatic hydrolysis

Trichoderma harzianum, Aspergillus sojae, and *S. cerevisiae.* The hydrolysis of apple pomace was carried out with 4% phosphoric acid at a ratio of 1:10 solid/liquid (w/v) at 110 °C for 40 min. The hydrolysate was fermented at 30 °C under anaerobic conditions and the highest bioethanol concentration

(8.7 g/L) was obtained after 5 days. Pathania et al. (2017) used apple pomace for bioethanol production by pretreatment of biomass with microwave irradiation which causes removal of a significant part of lignin, degradation of cellulose and hemicellulose, and improves the enzymatic hydrolysis. The pretreated apple pomace was hydrolyzed using multiple carbohydrases (cellulase, xylanase, amylase, and pectinase) which were produced by the fungus *Rhizopus delemar* F_2. The hydrolysate was inoculated with *S. cerevisiae* and *S. stipitis* cells immobilized in calcium alginate beads and produced 44.5 g/L bioethanol. Demiray et al. (2021) investigated that the utilization of soluble soy protein improved the enzymatic hydrolysis of apple pomace and the bioethanol production increased to 53.1 g/L.

Kumar et al. (2020) used apple pomace as substrate for bioethanol production by co-culture of *S. cerevisiae* and *Actinomyces* APW-12 which produces cellulase and xylanase and found maximum bioethanol concentration of 49.6 g/L. Cherian et al. (2015) reported a bioethanol concentration of 13.6 g/L from apple waste through SSF process. When cashew apple pulp used as substrate an ethanol yield of 0.5 g/g sugar was achieved (Shenoy et al. 2011). In this case, the pulp was treated with 2% sulfuric acid at 120 °C for 10 min followed by further 90 min at 90 °C to solubilize the pulp. Seluy et al. (2018) utilized cider waste to produce bioethanol. It is formed during cider production through alcoholic fermentation of apple juice by yeasts that naturally occur in the fruit. The cider waste exhibits a high Chemical Oxygen Demand (COD) greater than 170,000 mg O_2/l and represents about 10% of the volume of cider produced. The results showed that when the cider waste was supplemented with corn steep water at a concentration of 2.5% (v/v) the bioethanol production was 70.0 g/L.

Grape pomace is the residue from musts and wine elaboration. Rodriguez et al. (2010) used solid-state fermentation to produce bioethanol from grape pomace by *S. cerevisiae*. The fermentation was carried out under anaerobic conditions at 28 °C. The maximum bioethanol yield was 0.42 g/g sugar consumed after 48 h of incubation.

2.6.3 Banana wastes

Banana is a tropical crop from the *Musaceae* family. It is the most important fruit crop in the world, in terms of metric tons harvested. About 56% of global production occurred in Asia and 26% in the Americas (Guerrero et al. 2018; Guerrero and Munoz 2018). Banana fruit and its associated residual biomass consisted of starch and lignocellulosic materials. They need to be converted into glucose, which is then fermented into bioethanol. This is achieved using enzymatic hydrolysis or acid hydrolysis with inorganic acids (Velasquez-Arredondo et al. 2010). Banana peel waste is consisted of cellulose 28.92%, hemicellulose 25.23%, and lignin 10.56% (Prakash et al. 2018). Saccharification of banana peel is the most significant step for bioethanol production.

Prakash et al. (2018) utilized banana peel waste for bioethanol production using a cocktail of thermo-alkali-stable depolymerizing enzymes. In this case, a maximum bioethanol concentration of 21.1 g/L was obtained. In another work, banana peduncle waste was used as substrate for bioethanol production by *K. marxianus* after hydrolysis of the feedstock with various concentrations of H_2SO_4 (1–3%) at 150 °C for converting the lignocellulosic material to monomeric sugars (Sathendra et al. 2019). The highest bioethanol concentration (21.8 g/L) was achieved at 40 °C and pH 4.5 in batch fermentation.

2.6.4 Pineapple wastes

Pineapple is the second-ranked tropical fruit in terms of importance in world production (Casabar et al. 2019). It is used by several industrial companies due to its useful compounds such as citric acid, bromelain, antioxidants, and fermentable sugars (Gil and Maupoey 2018; Casabar et al. 2019). The utilization of pineapple in the industry, generates significant amounts of wastes consisted of peel, core, and crown. They represent about 50% of the total processed fruit (Conesa et al. 2016, 2018). The liquid phase of this residue contains glucose, fructose, and sucrose while the solid phase consists of lignin (16%), cellulose (35%), and hemicellulose (19%) (Conesa et al. 2016, 2018). Pineapple peel waste (PPW) is a good substrate for bioethanol production, since cellulose and hemicellulose are hydrolyzed to simple sugars (Conesa et al. 2018).

Conesa et al. (2016, 2018) investigated the production of bioethanol from pineapple wastes using microwave pretreatment of the feedstock or treated at 121 °C for 20 min following enzymatic hydrolysis

with a mixture of cellulase and hemicellulase from *A. niger* or cellulase from *A. niger* and *Trichoderma reesei* combined with *A. niger* hemicellulase. Several researchers have studied the bioethanol production from pineapple wastes and reported a bioethanol production of 5.4% (v/v) and an ethanol yield of 0.47 g/g sugar consumed (Gil and Maupoey 2018; Dominguez-Bocanegra et al. 2015). In another study, PPW used as substrate for bioethanol production by Casabar et al. (2019). A maximum bioethanol concentration of 5.98 g/L was achieved when *Trichoderma harzianum*was used for hydrolysis of the substrate and *S. cerevisiae* for the fermentation of sugars to ethanol.

2.6.5 Pomegranate peel waste

Pomegranate (*Punicagranatum* L.) is consumed as an edible fruit or juice. The global production of pomegranate is reached around 2 million tons. The extraction of juice from pomegranate in industrial scale generates large amounts of peel wastes as the juice yield is lower than half of the fruit weight (Roukas and Kotzekidou 2020b). The pomegranate peel waste (PPW) is used for the production of pectin, phenolic compounds, carotenoids, flavonoids, vitamin C, fertilizers, dietary fibers, tannins, reducing sugars, and biochar (Roukas and Kotzekidou 2020b).

Talekar et al. (2018) reported that 500–550 kg PPW are generated from 1 ton of fresh pomegranates after extraction of juice. In this work, the authors studied the bioethanol production from PPW using hydrothermal treatment at 115 °C for 40 min and found a maximum bioethanol concentration of 80 g /kg dry waste. PPW used for bioethanol production by Demiray et al. (2018) after hydrolysis with 1% (v/v) H_2SO_4 at 121 °C for 15 min. The hydrolysate was supplemented with nitrogen sources and metal salts and fermented by *S. cerevisiae* which produced 5.6 g/L bioethanol after 12 h of the fermentation. In another work (Demiray et al. 2019), the authors improved the bioethanol production from PPW using acid hydrolysis with 1% H_2SO_4 and enzymatic hydrolysis with cellulase at 50 °C for 72 h. In this case, the bioethanol concentration increased to 14.3 g/L by the yeast *K. marxianus* after 96 h of incubation.

2.6.6 Date, mango, and coconut wastes

Date wastes (which correspond to 10–50% of the annual date production—depending on the country) could be converted to biofuels. The amount of date fruit wastes depends on the appropriate harvest time and practices, as well as the efficient grading and packaging (Taghizadeh-Alisaraei et al. 2019a, b). The date wastes consist of glucose, fructose, sucrose, fibers, minerals, amino acids, and vitamins. The date wastes syrup is produced by heating the date wastes at 85 °C for 45 min with continuous stirring (Taghizadeh-Alisaraei et al. 2019a, b; Acourene and Ammouche 2012). Acourene and Ammouche (2012) studied the bioethanol production from date wastes syrup (180.0 g/L initial sugars) supplemented with 1.0 g/L ammonium phosphate and inoculated by *S. cerevisiae* at a ratio of 4% (w/v). The results showed a maximum bioethanol concentration of 136.0 g/L after 72 h of the fermentation.

Mango waste is treated for use as dietary fibers, substances with health-promoting phytochemicals, and nutritional supplements with antioxidant, anti-inflammatory, and immunomodulatory properties (Carrillo-Nieves et al. 2017). In the mango processing industry, mango bark residue is generated during the production of nutritional supplements. Carrillo-Nieves et al. (2017) investigated the bioethanol production from mango stem bark residue pretreated with 3% NaOH at 120 °C for 15 min followed by SSF process using cellulase, β-glucosidase and a 4% (v/v) inoculum of *S. cerevisiae.* The results showed a maximum bioethanol yield of 81.6% of the theoretical. Another popular fruit is the mangosteen, well known for the excellent flavor. Mangosteen pericarp waste (MPW) is a byproduct of mangosteen process. According to FAO, about 30.8 million tons of MPW are generated annually (Cho et al. 2020). Cho et al. (2020) used MPW for production of bioethanol after popping pretreatment and enzymatic hydrolysis with cellulase and pectinase at 45 °C for 30 min. The hydrolysate was fermented by *S. cerevisiae* at 32 °C in shake flasks. A maximum ethanol yield of 75% of theoretical was obtained after 48 h of incubation.

The main waste of the coconut processing is the coconut meal which is generated after coconut milk processing. It contains 10–20% oil which is used for the production of biodiesel. After oil extraction, the residue contains 16% cellulose and 34%

hemicellulose (Sangkharak et al. 2020). It was used for the production of bioethanol after pretreatment with 50% NaOH at 121 °C for 40 min. The pretreated substrate was hydrolyzed with cellulase and the hydrolysate was inoculated with *S. cerevisiae* cells at a ratio of 10%. The maximum bioethanol concentration was 8.5 g/L after 60 h of the fermentation (Sangkharak et al. 2020).

2.6.7 Soft drink wastewaters

Sugar-sweetened beverage wastewaters are produced in large quantities in proportion to the high production of these beverages, as some of them contain high sugar concentration (6–18% w/v) (Isla et al. 2013; Comelli et al. 2016a). The sugars consist of glucose, fructose, and sucrose which can be used directly in fermentations without any pretreatment (Comelli et al. 2016b). The soft drink industry produces approximately 75% of all sugar-sweetened beverages. A portion of the beverages produced is discarded due to quality control practices or is returned from retail stores due to lack of gas or expired product (Comelli et al. 2016b).

Isla et al. (2013) examined the bioethanol production from different types of soft drink wastewaters (SDWW) supplemented with 15.0 g/L yeast extract. An ethanol yield of 0.39, 0.42, and 0.51 g/g sugar consumed was achieved when *S. cerevisiae* var. Windsor was grown on lemon-lime, orange, and cola soft drink, respectively. In other similar works, Comelli et al.(2016a,b) enriched SDWW with a supplement consisted of inorganic salts (i.e. $MgSO_4{\cdot}7H_2O$, $(NH_4)_2HPO_4$, and $ZnSO_4{\cdot}7H_2O$) in order to produce bioethanol. An ethanol yield of 0.42 and 0.44 g/g sugar consumed was obtained when *S. cerevisiae* var. Windsor and *Saccharomyces bayanus* were grown on the above substrate, respectively. A schematic diagram of bioethanol production from fruit industry wastes is shown in Fig. 5.

2.7 Oil industry wastes

2.7.1 Olive oil processing wastes

The traditional oil industry generates two byproducts at the end of the process: the olive mill solid waste (OMSW) and the olive mill wastewater (OMW) which cause serious environmental pollution problems (Nikolaou and Kourkoutas 2018; Abu Tayeh et al. 2014, 2016, 2020). OMSW is a mixture of skin, pulp, and seeds. OMSW is consisted of (% w/w of dry matter): lignin 37, cellulose and hemicellulose 49.5, olive oil 7.5, and mineral substances 6.0 (Battista et al. 2016). The global annual production is about $4X10^8$ kg of dry matter (Abu Tayeh et al. 2016). OMW is the liquid which is formed during olive oil production. OMW is consisted of (% w/w): water 90.0, organic compounds 8.5, and mineral salts 0.4–2.5 (Battista et al. 2016). The total annual production of OMW is higher than $3X10^7$ m^3 (Nikolaou and Kourkoutas 2018). OMSW and OMW contain high concentrations in phenolic compounds (Battista et al. 2016; Solomakou and Goula 2021).

Abu Tayeh et al. (2014, 2016, 2020) investigated the production of bioethanol from OMSW pretreated with 2% (v/v) sulfuric acid at 100 °C for 2 h, hydrothermal pretreatment with water and 0.6 M formic acid at 140–170 °C and pressure 10–13 atm for 1 h, and microwave pretreatment with 0.6 M formic acid at 140 °C for 10 min followed by enzymatic hydrolysis with a mixture of cellulase and β-glucosidase at 50 °C for 24 h. The maximum bioethanol concentration (15.9 g/L) was obtained in OMSW microwave pretreated. Battista et al. (2016) reported a maximum bioethanol concentration of 9.0 g/L when a mixture of olive pomace (OP) and OMW used as feedstock after pretreatment with 0.5% (v/v) H_2SO_4 at 120 °C for 30 min and 3 M NaOH at pH of 12.0 for 24 h. Ngoie et al. (2020) utilized wastewater sludge from the edible oil industry as a novel feedstock for bioethanol production after extraction of remained oil in the sludge. The residue was autoclaved at 121 °C for 15 min, dried at 80 °C for 24 h and hydrolyzed using cellulase at 50 °C for 24 h. The hydrolysate used as substrate for bioethanol production by *S. cerevisiae*. In this case, a maximum bioethanol yield of 106% of theoretical was obtained. Sarris et al. (2014) and Nikolaou and Kourkoutas (2018) used a mixture of OMW and beet molasses for bioethanol production by free and immobilized *S. cerevisiae* cells and found a maximum bioethanol concentration of 41.8 and 61.2 g/L, respectively.

2.7.2 Palm oil processing wastes

During palm oil production, palm oil mill effluent (POME) is generated. It was reported that an average of 52.6–55.4 million tons of POME is generated for

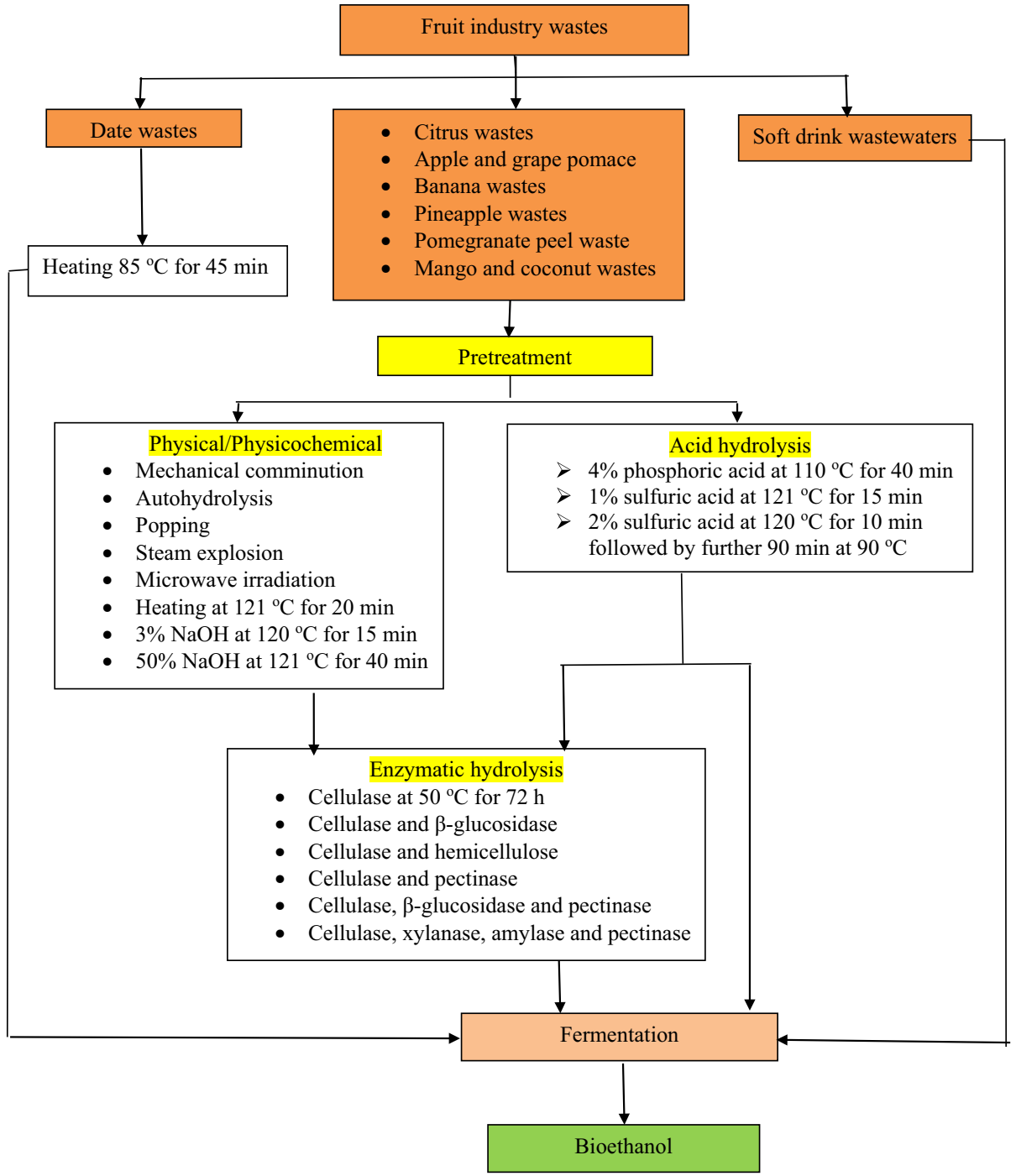


Fig. 5 Bioethanol production from fruit industry wastes using different pretreatment methods and enzymatic hydrolysis

each ton of crude palm oil produced. POME contains organic compounds, carbohydrates, proteins, lipids, nitrogenous compounds and minerals (Samsudin and Mat Don 2015). Another residue is the oil palm trunk (OPT) which contains fibrous vascular bundles and powdery parenchyma and is consisted of lignin, cellulose, hemicellulose, protein, fat, and minerals.

Samsudin and Mat Don (2015) investigated the bioethanol production from a mixture of OPT sap and POME by the yeast *S. cerevisiae* and found a maximum bioethanol yield of 0.464 g/g glucose utilized. In another interesting study two pretreatment techniques (using H_2SO_4 or NaOH) were compared for producing bioethanol from empty fruit bunches (EFBs) from oil pulm tree (Chiesa and Gnansounou 2014). EFBs contain high concentration of polysaccharides, mainly cellulose, that must be broken down to fermentable sugars after pretreatment and enzymatic hydrolysis. Better results were obtained when the EFBs was treated with 1.51% (v/v) H_2SO_4 at 161.5 °C for 9.44 min followed by enzymatic hydrolysis with cellulase and β-glucosidase. In this case, a high glucose yield of 85.5% was observed which can be used for the production of high bioethanol concentration (Chiesa and Gnansounou 2014). The bioethanol production from oil industry wastes is presented in Fig. 6.

2.8 Coffee industry wastes

Coffee is one of the most consumed beverages in the world with an amount of million bags of 60 kg produced every year (Yadira et al. 2014; Tehrani et al. 2015; Choi et al. 2012; Kim et al. 2017). During the coffee processing steps, large amounts of different wastes are generated such as coffee residue (CR) (Tehrani et al. 2015; Choi et al. 2012; Kim et al. 2017), pulp (Akbas and Stark 2016; Menezes et al. 2014), husk (Akbas and Stark 2016; Dadi et al. 2018), spent coffee ground (SCG) (Dadi et al. 2018; Ravindran et al. 2017; Mussatto et al. 2012), silver skin (SS) (Dadi et al. 2018; Mussatto et al. 2012), mucilage (Yadira et al. 2014), and wastewater (Akbas and Stark 2016). CR waste is generated after coffee extraction for coffee powder and instant coffee preparation (Choi et al. 2012). It contains cellulose, hemicellulose, lignin, carbohydrates (glucose, galactose, mannose), and lipids (Tehrani et al. 2015; Kim et al. 2017). CR examined as feedstock for bioethanol production by Choi et al. (2012) and Kim et al. (2017) after popping pretreatment at 1.47 MPa for 10 min or acid-chlorite pretreatment at 80 °C for 1 h followed by enzymatic hydrolysis. An ethanol yield of 87.2% and 73.8% of theoretical was obtained when the substrate was treated at high pressure and acid-chlorite pretreatment, respectively.

During the coffee production, pulp and coffee husk wastes are generated applying the wet and dry process to produce green grains, respectively (Menezes et al. 2014). Coffee pulp hydrolysate contains a variety of fermentable sugars such as glucose, fructose, sucrose, maltose, xylose, and arabinose (Akbas and Stark 2016). Menezes et al. (2014) investigated the bioethanol production from coffee pulp pretreated with 4% (w/v) NaOH at 121 °C for 25 min followed by enzymatic hydrolysis with Celluclast 1.5L (Novozymes) at 50 °C for 72 h. The results indicated a maximum bioethanol concentration of 13.6 g/L with a yield of 0.4 g/g glucose utilized. Coffee SS and SCG are generated during the beans roasting and instant coffee preparation, respectively (Mussatto et al. 2012). SCG and husk used for bioethanol production by Dadi et al. (2018) after acid hydrolysis with 3% (v/v) H_2SO_4 at 121 °C for 20 min followed by enzymatic hydrolysis with cellulases and β-glucosidases at 50 °C for 48 h. The hydrolysate was fermented by the lignocellulosic yeast GSE16-T18 followed by purification using pervaporation membrane resulted in a bioethanol yield of 51.7 and 132.2 g/L for SCG and husk, respectively. Ravindran et al. (2017) found a novel pretreatment for spent coffee waste (SCW) to produce high bioethanol concentration. SCW was pretreated with 4% $KMnO_4$ followed by treatment to ultrasound radiation for 20 min. This treatment resulted in 98% cellulose recovery, a maximum lignin removal of 46%, and an increase in reducing sugars yield after enzymatic hydrolysis. The results indicate that SCW could be utilized for bioethanol production.

2.9 Brewery, vegetable, and milk indusry wastes

In the brewery industry, two mainly byproducts are generated during beer production. The brewer's spent grain waste (BSGW) (Pinheiro et al. 2019) and the beer fermentation broth waste (BFBW) (Ha et al. 2012; Khattak et al. 2013). BSGW is a solid generated during the mashing process and represents about 85% of brewing industry wastes (20 kg of BSGW are generated per 100 L of beer produced) (Pinheiro et al. 2019). In Europe are produced approximately 3.5 million tons of BSGW per year. It consists of cellulose (12–25%), hemicellulose (19–42%), lignin (15–27%), and protein (14–31%) (Pinheiro et al. 2019). An interesting study on bioethanol production from BSGW reported by Pinheiro et al. (2019). In this

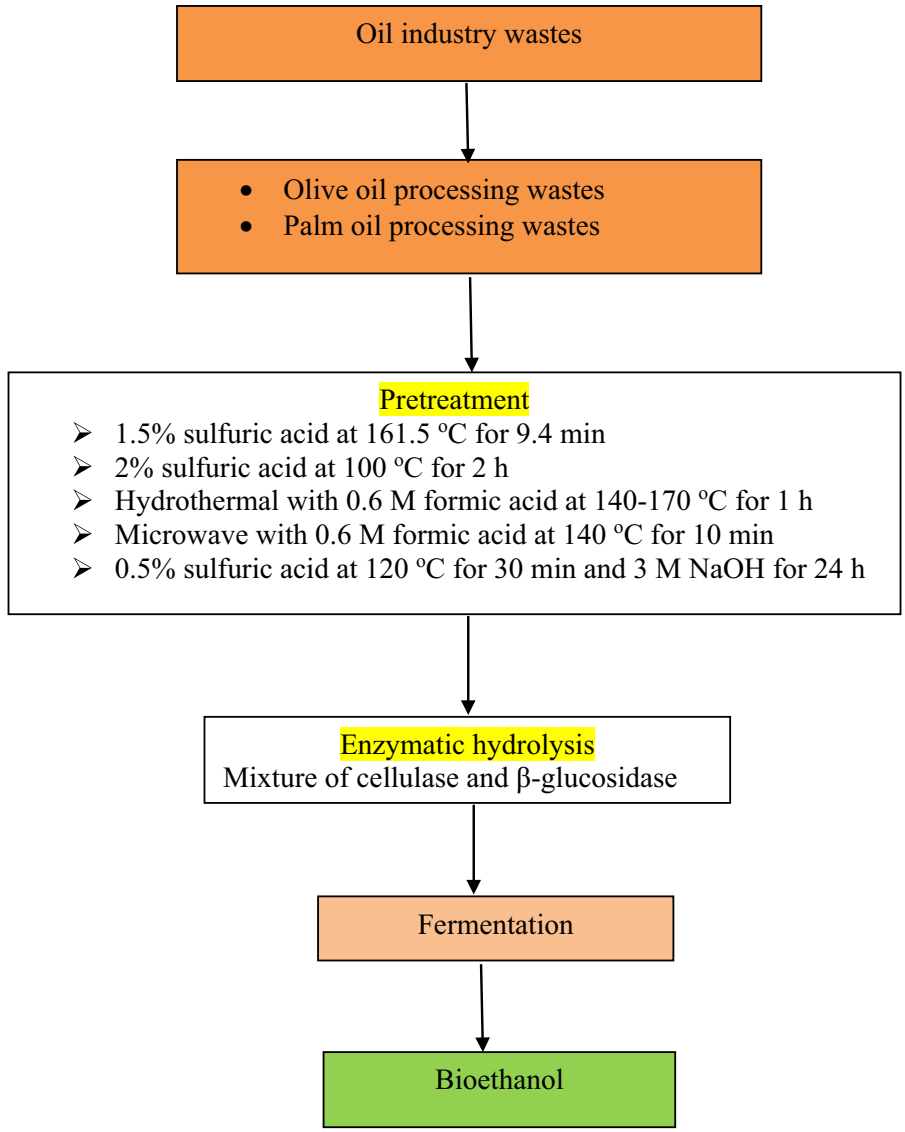


Fig. 6 Bioethanol production from olive and palm oil processing wastes treated with chemical/physicochemical methods and enzymatic hydrolysis

work, BSGW whole slurry at 25% solid loading pretreated at 150–170 °C for 5 min followed by enzymatic hydrolysis with a commercial cellulase mixture (Cellic CTec2 from *Trichoderma reesei*) at 50 °C for 120 h. The hydrolysate was fermented by the yeast *S. cerevisiae* BLGII 1762 at 30 °C in shake flasks at 150 rpm. The highest bioethanol concentration (42.3 g/L) was achieved after 48 h of incubation.

BFBW is the wet solid sediment obtained after beer production and represents about 5% of the fermentation broth. It contains 75% liquid and the residual yeast cells (Ha et al. 2012; Khattak et al. 2013). The supernatant from BFBW contains high amounts of carbon, nitrogen, and other substances such as enzymes and yeast cells. The enzymes are derived from malted barley during beer fermentation and are suitable for the saccharification process (Ha et al. 2012). Khattak et al. (2013) reported the production of bioethanol via simultaneous saccharification and fermentation from BFBW supernatant in two phases. In the first phase by gradual increase in temperature from 25 to 67 °C the production of bioethanol was up to

102.5 g/L while in the second phase at 67 °C when an additional 3% BFBW was added into the substrate the concentration reached to 219.0 g/l.

2.9.1 Vegetable industry wastes

In the vegetable processing industry, the main byproducts which are generated and used for bioethanol production are the tomato pomace (TP), carrot pomace (CP), and cruciferous vegetable residue (CVR). In the tomato industry, tomato pomace is the residue which is generated during the processing of tomatoes to produce juice, paste, sauce, puree, and ketchup (Hijosa-Valsero et al. 2019; Lenucci et al. 2013). It is composed of skins, seeds, and vascular tissues and represents about 4% of the whole fruit weight (Lenucci et al. 2013). TP contains starch, cellulose, hemicellulose, lignin, pectin, protein, fat, and inorganic elements such as Ca, K, Mg, Na, P, Fe, Mn, and Cu (Hijosa-Valsero et al. 2019). Hijosa-Valsero et al. (2019) investigated the bioethanol production from TP pretreated with hydrothermal process at 121 °C for 20 min followed by enzymatic hydrolysis at 50 °C for 120 h using a mixture of cellulase and endo-β-1,4-glucanase. The hydrolysate was fermented by different strains of yeasts and bacteria and a maximum bioethanol concentration of 20.1–21.7 g/L was obtained.

Carrot pomace (CP) is a residue which is generated during the extraction of juice from the carrot. It consists of 28% cellulose, 6.7% hemicellulose, 17.5% lignin, and 2.1% pectin (Yu et al. 2013). Yu et al. (2013) used CP as substrate for bioethanol production after enzymatic hydrolysis with a mixture of enzymes Accellerase^{TM} 1000 and pectinase at 50 °C for 84 h. The fermentation was performed at 42 °C with the thermotolerant yeast *K. marxianus.* The highest bioethanol concentration was 37 g/L. In another work, Demiray et al. (2016) reported a maximum bioethanol concentration of 6.91 g/L after 72 h of incubation when *S. cerevisiae* was grown on 12% CP supplemented with 0.1% $(NH_4)_2SO_4$.

Cruciferous vegetables (cabbage, broccoli, and turnip) are among the agricultural crops which are produced in the largest amounts (Song et al. 2017). A large quantity of cruciferous vegetables residue (CVR) is generated during harvest and downstream production process of these crops. CVR can be converted into biofuels and other valuable products in order to reduce pollution and reinvigorate the agricultural economy (Song et al. 2017). CVR used as substrate for bioethanol production after enzymatic hydrolysis with cellulase and pectinase at 37 °C for 48 h followed by fermentation with the yeast *S. cerevisiae* at 32 °C for 48 h. The results showed a maximum bioethanol yield of 85.7% of the theoretical (Song et al. 2017).

2.9.2 Milk industry wastes

An important byproduct of cheese production is the cheese whey. It is produced in large amounts and is a significant source of environmental pollution (Akbas and Stark 2016; Zhou et al. 2019). It has a very high Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) which are varied between 40,000–60,000 and 50,000–80,000 mg/L, respectively (Ryan and Walsh 2016). The total worldwide production of cheese whey is about 185 million tons per year. It contains 4.5–5.0% lactose, 0.6–1.0% soluble proteins, 0.4–0.5% lipids, and 6–10% mineral salts (Zhou et al. 2019). Cheese whey powder (CWP) is a concentrated form of cheese whey and it contains 70% lactose, 11% proteins, 7.2% moisture, and 4% ash (Zhou et al. 2019).

Zhou et al. (2019) studied the production of bioethanol from CWP after enzymatic hydrolysis with β-galactosidase at 55 °C for 72 h in order to hydrolyze lactose to glucose and galactose. The hydrolysate was fermented by *S. cerevisiae* and an ethanol yield of 110 g/kg CWP was produced. Wagner et al. (2014) reported the conversion of the remaining lactose in the delactosed cheese whey (DCW) after electrodialysis to bioethanol by the yeast *K. marxianus.* The results showed a maximum bioethanol concentration of 11% (v/v) after 52 h of the fermentation. Ryan and Walsh (2016) reported the production of bioethanol from whey permeate containing 8% lactose (after concentration by reverse osmosis) by reuse the yeast *K. marxianus* in repeated batch fermentation. In this case, the bioethanol levels range from 2.5 to 4.2% (v/v).

Another byproduct of the milk industry is the soybean waste (okara). It is a byproduct which is generated during the processing of soymilk, tofu, and their derivatives (Choi et al. 2015a, b). It contains cellulose, hemicellulose, and pectin. About 14 million tons of okara are generated annually worldwide. Choi et al. (2015a, b) used okara as substrate for bioethanol production after pretreatment at 121 °C for 20 min

and enzymatic hydrolysis at 37 °C for 72 h. The hydrolysate was fermented by *S. cerevisiae* and the maximum bioethanol yield was 96.2% of the theoretical. The bioethanol production from milk industry wastes is presented in Fig. 7.

In Table 1 is presented the worldwide production per year of some important food industry wastes used for the production of bioethanol. The feedstocks producing the highest bioethanol concentration as well as the pretreatment method, microorganism, fermentation mode, and bioethanol concentration are summarized in Tables 2 and 3. As shown in Table 2, the food industry wastes produce large amounts of bioethanol in batch fermentation (21.0–219.0 g/L).

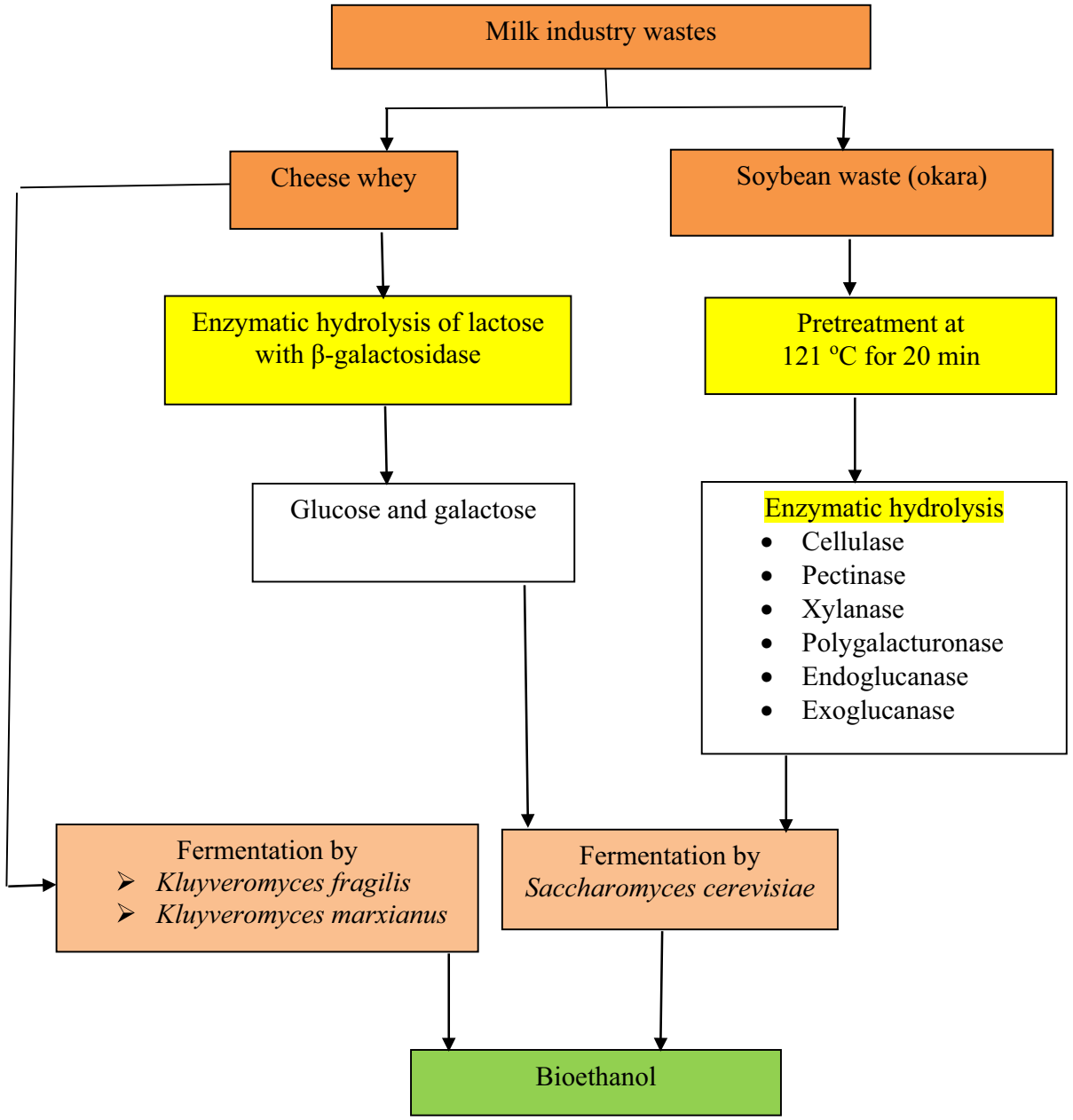


Fig. 7 Bioethanol production from cheese whey and soybean waste (okara) by different strains of *S. cerevisiae, K. fragilis,* and *K. marxianus*

Table 1 Global annual production of some important food industry wastes used for bioethanol production

Food industry wastes	Global annual production (million tons)	References
Sugarcane bagasse	279.0	Jugwanth et al. (2020)
Cheese whey	185.0	Zhou et al. (2019)
Potato wastes	108.0	Akbas and Stark (2016)
Coconut meal	44.0	Sangkharak et al. (2020)
Olive oil mill wastewater	31.5	Nikolaou and Kourkoutas (2018)
Palm wastes (oil palm and date palm)	30.0	Taghizadeh-Alisaraei et al. (2019a, b)
Cassava peel waste	14.0	Aruwajoye et al. (2020)
Soybean waste (okara)	14.0	Choi et al. (2015a, b)
Citrus peel waste	10.0	Jeong et al. (2021)
Olive mill solid waste	9.6	Abu Tayeh et al. (2020)
Apple pomace	8.0	Evcan and Tari (2015)
Tomato pomace	7.3	Hijosa-Valsero et al. (2019)
Pineapple wastes	0.6	Casabar et al. (2019)

The utilization of some feedstocks such as beer fermentation broth waste, date waste syrup, potato waste, and cane molasses results to enhanced bioethanol concentration (121.0–219.0 g/L). In repeated-batch fermentation, high yields of bioethanol (15.1–98.6 g/L) were obtained by valorization of cane and beet molasses, sugarcane bagasse, and corncob residue (Table 3). In fermentations carried out by *S. cerevisiae* cells immobilized on different matrices high bioethanol yield retained for a long time (11–60 days). In case of the rotary biofilm reactor, the biofilm of baker's yeast formed on the discs of the reactor retained the ability to produce bioethanol for 60 days (Table 3). The results presented in Tables 2 and 3 show that the food industry wastes could be evaluated as useful substrates for bioethanol production in batch and repeated-batch fermentation.

3 Conclusion and future prospects

Food industry wastes are produced in large quantities worldwide and cause serious environmental problems. The conversion of a lignocellulosic substance into bioethanol includes three steps: pretreatment, enzymatic hydrolysis, and fermentation. This review provides a detailed overview of the current knowledge on the above treatments. The problems shown during bioethanol production from food industry wastes should be overcome in order to decrease the production cost. Further research is needed to identify most efficient processes to achieve economically feasible bioethanol production. Some alternative treatments have been proposed in order to overcome the problems, which appear during bioethanol production from food industry wastes. But, the high economic costs of these technologies and the complex substrates used make difficult the applications of these treatments in industrial scale.

The most important challenges of the current pretreatment technologies concern: (1) the detection of a capable microorganism or co-culture of microorganisms producing the appropriate enzymes to break down the lignocellulosic materials into sugar monomers in order to obtain high bioethanol concentration in one step, and (2) the selection of genetically modified microorganisms to ferment directly the lignocellulosic materials of the food industry wastes to high bioethanol yield in order to reduce the cost of the process. There are promising technologies for the fully commercialization of bioethanol production from food industry wastes. The future promising technology for bioethanol production is the SSF process using co-culture of microorganisms to hydrolyze the lignocellulosic material and convert the simple sugars into bioethanol. This process is greener, safer, and decreases the total production cost. Moreover, it is sustainable as the production of bioethanol is

Table 2 Pretreatment methods, microorganisms, fermentation mode, and fermentation conditions used for the production of high bioethanol concentration from food industry wastes in batch fermentation

Substrate	Pretreatment of substrate	Microorganism	Fermentation mode	Bioethanol (g/L)	References
Sugarcane bagasse	Alkali treatment	*K. marxianus*	100 L rotary drum reactor (SSF process, pH 5.0, 42 °C, 5 rpm)	24.6	Lin et al. (2013)
Soybean waste (okara)	Hydrothermal process and enzymatic hydrolysis	*S. cerevisiae*	5 L fermenter (pH 5.0, 30 °C, 300 rpm)	59.0	Choi et al. (2015a, b)
Date waste syrup	Non-treated	*S. cerevisiae*	3 L fermenter (pH 4.5, 30 °C, static fermentation)	136.0	Acourene and Ammouche (2012)
Cane molasses	Non-treated	Baker's yeast	2 L fermenter (pH 4.3, 30 °C, 100 rpm, aeration rate 0.3 vvm)	121.0	Jayus et al. (2016)
Carrot pomace	Non-treated	*K. marxianus*	1 L jar fermenter (SSF process, pH 5.0, 42 °C, 680 rpm)	37.0	Yu et al. (2013)
Beer fermentation broth waste	Non-treated	*S. cerevisiae*	0.8 L jar fermenter (pH 5.2, 25–67 °C, 50 rpm)	219.0	Khattak et al. (2013)
Bakery wastes	Enzymatic hydrolysis	*S. cerevisiae*	0.5 L fermenter (pH 5.5, 30 °C, 400 rpm)	46.6	Han et al. (2019)
Coffee waste (husk)	Acid and enzymatic hydrolysis	*S. cerevisiae*	Shaker incubator (pH 5.0, 30 °C, 100 rpm)	132.2	Dadi et al. (2018)
Potato waste	Non-treated	Co-culture *A. niger* and *S. cerevisiae*	Shaker incubator (pH 6.0, 30 °C, 150 rpm)	125.0	Pinaki and Lhakpa (2016)
Delactosed whey permeate	Electrodialysis	K. marxianus	Shaker incubator (pH 5.5, 30 °C, 100 rpm)	86.8	Wagner et al. (2014)
Orange peel waste hydrolysate	Non-treated	S. cerevisiae	Shaker incubator (pH 4.8, 37 °C, 100 rpm)	72.0	Kyriakou et al. (2019)
Brewer's spent grain waste	Autohydrolysis and enzymatic hydrolysis	S. cerevisiae	Shaker incubator (pH 4.8, 30 °C, 150 rpm)	42.3	Pinheiro et al. (2019)
Cheese whey powder	Enzymatic hydrolysis	S. cerevisiae	Shaker incubator (pH 5.5, 30 °C, 150 rpm)	22.0	Zhou et al. (2019)
Tomato pomace	Hydrothermal process and enzymatic hydrolysis	S. cerevisiae	Shaker incubator (pH 5.0, 30 °C, 150 rpm)	21.0	Hijosa-Valsero et al. (2019)
Sweet potato residues	Enzymatic hydrolysis	S. cerevisiae	Erlenmeyer flask (static fermentation, pH 4.8, 30 °C)	79.0	Wang et al. (2016)
Deoiled rice bran	Non-treated	S. cerevisiae	Erlenmeyer flask (static fermentation, pH 6.0, 30 °C)	76.4	Agrawal et al. (2019)
Cassava peel waste	Acid hydrolysis	S. cerevisiae	Erlenmeyer flask (static fermentation, pH 4.0–6.0, 20 °C)	28.2	Abidin et al. (2014)
Apple pomace	Non-treated	*S. cerevisiae* and A. APW-12	Erlenmeyer flask (SSF process, pH 6.0, 30 °C)	49.6	Kumar et al. (2020)
Pineapple waste	Non-treated	*S. bayanus*	Erlenmeyer flask (SSF process, pH 5.0, 28 °C)	42.6	Gil and Maupoey (2018)

Table 3 Food industry wastes used for bioethanol production by recycling free or immobilized yeast cells in repeat-batch fermentation

Substrate	Pretreatment of substrate	Microorganism	Fermentation mode	Bioethanol (g/L)	Stability of fermentation system (days)	References
Beet molasses	Non-treated	Immobilized baker's yeast on discs	12 L rotary biofilm reactor (pH 5.0, 30 °C, 40 rpm)	52.3	60	Roukas and Kotzekidou (2020a)
Blackstrap molasses	Non-treated	Immobilized *S. cerevisiae* cells on thin-shell silk cocoons	Shaker incubator (pH 5.0, 33 °C, 150 rpm)	98.6	10	Rattanapan et al. (2011)
Cane molasses	Non-treated	Immobilized *S. cerevisiae* cells on sugarcane bagasse	3 L packed bed reactor (pH 4.8, 30 °C)	97.0	10	Sowatad and Todhanakasem (2020)
Sugarcane bagasse	Microwave alkali treated and enzymatic hydrolysis	Immobilized *S. cerevisiae* cells on sugarcane bagasse	Erlenmeyer flask (static fermentation, pH 5.0, 30 °C)	15.1	11	Singh et al. (2013)
Sugarcane bagasse	Phosphoric acid treated, alkali delignification and enzymatic hydrolysis	*S. cerevisiae* (free cells)	1.5 L fermenter (pH 4.5, 32 °C, 150 rpm)	50.0	3	Silva et al. (2016)
Corncob residue	Enzymatic hydrolysis	*P. guilliermondii* (free cells)	Erlenmeyer flask (static fermentation, pH 5.0, 30 °C)	36.0	4	Fan et al. (2013)

based on the use of renewable and biological resources.

The promising food industry wastes for bioethanol production in large scale are the following: cane and beet molasses, date waste, and beer fermentation broth. The above feedstocks contain sugars which can be directly fermented to high bioethanol yield using different strains of *S. cerevisiae* without pretreatment of the substrate which is an expensive method and increases the final cost of the product. In addition, the cheese whey could be used as a promising food industry waste for the production of bioethanol for the reasons below: (1) it is produced in large amounts, (2) it is easily hydrolysed by the commercial enzyme β-galactosidase into simple sugars in order to be utilized by the yeast *S. cerevisiae* to produce high bioethanol concentration and (3) it can be utilized directly (without enzymatic hydrolysis) for bioethanol production by the yeasts *K. fragilis or K. marxianus.* In this case, the disadvantage is the low concentration of the product. This can be overcome after suitable selection of a genetically modified strain of the above yeasts. Also, the sugarcane bagasse, potato wastes, and fruit industry wastes which are produced in large amounts could be used for bioethanol production in industrial scale using co-culture of microorganisms for efficient bioethanol production with low cost.

Declarations

Conflict of interest The authors declare no conflict of interest.

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