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Review

Food Waste to Bioethanol: Opportunities and Challenges

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Abstract: The increasing global population will require sustainable means to sustain life and growth. The continuous depletion and increasing wastage of the energy resources will pose a challenge for the survival of the increasing population in the coming years. The bioconversion of waste generated at different stages of the food value chain to ethanol can provide a sustainable solution to the depleting energy resources and a sustainable way to address the growing food waste issue globally. The high carbohydrate and nitrogen content in the food waste can make it an ideal alternative substrate for developing a decentralized bioprocess. Optimizing the process can address the bottleneck issues viz. substrate collection and transport, pretreatment, fermentative organism, and product separation, which is required to make the process economic. The current review focuses on the opportunities and challenges for using the food loss and waste at different stages of the food value chain, its pretreatment, the fermentation process to produce bioethanol, and potential ways to improve the process economics. The impact of substrate, fermentative organisms' process development, downstream processing, and by-product stream to make the bioethanol production from the waste in the food value chain a commercial success are also discussed.

Keywords: bioethanol; food loos and waste; sustainable; fermentation; enzymes

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1. Introduction

As per an estimate, there will be an increased demand of food and energy resources for the 9.8 billion world population by 2050 [1–3]. The 2022 SDGs progress report mentioned that unsustainable patterns of consumption and production are the root cause of climate change, biodiversity loss and the increasing pollution [4]. There has been a global consensus on attaining and developing sustainable methods and habits to address these issues. In 2015, the United Nations set 17 Sustainable Development Goals (SDGs) for the peace and prosperity for people and the planet for the current and future generations, which included providing access to affordable and clean energy (SDG 7) and minimizing the food waste (SDG 12.3) [4]. The recent incidents such as COVID-19, Russia–Ukraine war, increased fuel prices, and unemployment worsened the situation by increasing the food prices in 47% of countries in 2020 vs. only 16% in 2019 and causing the crude oil prices to fluctuate drastically, with prices going as low as 20 USD/Bbl during COVID 19 and as high as 120 USD/Bbl during the Russia–Ukraine War [4,5]. The efforts and progress on the SDG goals is often challenged by such unfavorable events, thus aggravating the hunger problem, providing a more compelling reason to find alternative energy resources and better recover and reutilize the energy and resources lost in the food wasted.

The dire need of the several nations to become self-sufficient in terms of energy production led to the research and promotion of biofuels use. A strategic shift in this direction was seen post Arab Oil Embargo in 1973 when certain geopolitical situations led to an embargo on petroleum by the Organization of the Petroleum Exporting Countries (OPEC) resulting in increased petroleum prices four times [6,7]. The research on ethanol production from the food waste can be dated back to 1920 when the wastes from the production industry such as corn cannery waste and sugarcane molasses were considered to have potential for use in ethanol production [8]. During the course of biofuel development, numerous biofuels viz. methanol, methane, natural gas, propane, hydrogen, etc. have been researched. Owing to the remarkable chemical properties such as octane booster [9], lower toxic emissions [10], high latent heat of vaporization—361 Btu/lbs. (839.686 kJ/kg), and ease of integration into the current chassis, ethanol is considered as the best alternative fuel for automobiles currently [11]. The production of bioethanol is considered a mature technology with 15.8 billion gallons of fuel ethanol produced in 2017 in the USA [12]. The USA and Brazil currently lead the global ethanol production with the USA and Brazil producing about 15 and 7.5 billion gallons of ethanol, respectively, using the corn and sugarcane [13]. Any doubts on the success of bioethanol can be put to rest by comparing the number of successfully running biofuel plants globally. The majority of the ethanol production in the USA is carried with corn, and out of the 201 plants, 195 plants use corn as the feedstock for the bioethanol production [14]. The majority of the countries use feedstocks such as corn, sugarcane, sweet potato, sweet sorghum, potato, cassava, barley, fruits, wheat, and rice for bioethanol production due to the ease of obtaining the fermentable sugars [15]. Most of the above-mentioned feedstocks fall under the staple food category, and their use for bioenergy production had incited food vs. fuel issues [16]. To meet the biomass energy crop requirements of the external market, the usage of land, fertilizers, and water sources had been increasing, resulting in several agricultural, economic, environmental, and landmass constraints [17–19]. As a result of such complications with corn usage, the Chinese government restricted the use of corn for ethanol production since 2006 [20]. Furthermore, this becomes a challenge for the landlocked countries to utilize the available agricultural land for food or fuel. As the demand for bioethanol increases globally, a successful corn or sugarcane-based bioethanol production can create global price challenges similar to what is seen with the petroleum-based product. To address the issue, efforts have increased in the past decades to find economical, sustainable, and ubiquitously available substrates for bioethanol production. Several substrates viz. lignocellulosic biomass, algae, food waste, gases etc. have been researched, but none had been able to replicate the economic success achieved by corn or sugarcane-based bioethanol production.

Among the different substrates researched and tested, food waste is the most abundant, economic and ubiquitously available substrate that can be utilized for bioethanol production. Annually around 1.3 billion tons of food is wasted globally, resulting in the wastage of land, water, energy and input resources used for food production, leading to an economic loss of approximately 3.3 trillion USD [21–23]. As per the FAO's 2022 report, 3.1 billion people do not have access to a healthy diet, and the number of people affected by hunger increased from 150 million in 2019 to 828 million in 2021, and yet such huge amounts of food are wasted [24]. Increased urbanization, better living standards, poor agricultural, harvest, substandard processing and packaging practices and facilities, inefficient marketing information, unplanned buying are some of the key drivers for the production of enormous amount of food waste. As per an estimate, globally, about 13.3% of the food is lost after harvesting and before reaching the retail markets, and about 17% of the food produced is lost at the consumer level [4]. The energy lost in the food waste needs to be recovered to prevent economic losses.

The conventional methods of valorizing and recycling food waste had been to produce biogas via anaerobic digestion, recover energy by combustion, use in animal feed, or use for composting. Figure 1 shows the percentage distribution of the food waste toward different applications in) USA. Undeniably, these conventional methods had been peddled socially, economically and environmentally, but the conventional methods suffer several setbacks due to longer time intervals for energy generation (anaerobic digestion), intensive capital, energy inputs, persistent organic pollutant (POPs) production (combustion), propensity to harbor pathogenic microbes (animal feed), unpleasant odor, and GHGs production (composting) [25–27]. According to a study, 95% of the total generated food waste is directed toward the landfills sites, releasing 3.3 billion tons of CO_2 per year, making it the third top greenhouse gases (GHG) emitter after the USA and China [22,28]. In the USA, it was the second largest category of the municipal solid waste (MSW) collected in the year 2015 [29]. The large amount of FLW generated usually ends up at the landfill sites, which creates challenges viz. waste management, pollution and economic loss. The sea food waste comprising viscera, fins, scale, bones, etc. can produce bad odors and biogenic amine that pollutes coastal and marine environments impacting the coastal, sea and coral life [30].

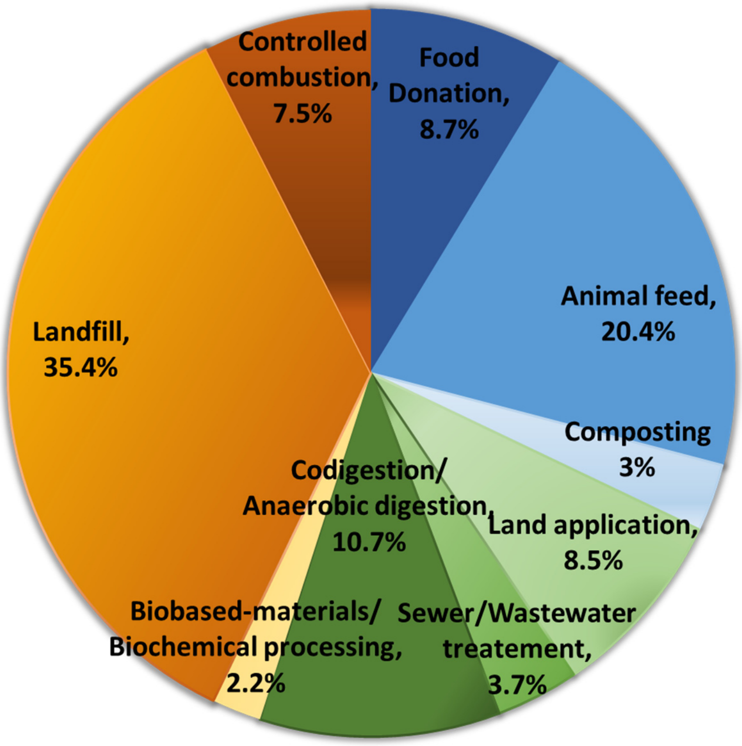

Figure 1. Percentage distribution of excess food and food waste management in U.S.A. generated in the industrial, residential, commercial and institutional sectors, 2016 [31]. Landfill, incineration, composting, anaerobic digestion, pyrolysis, animal feed, biochemical processing, are some of the methods that have been employed to recover the energy in food waste [32].

Food waste is a rich biomass harboring 35.5–69% carbohydrates, 3.9–21.9% proteins, oils and fats, and organic acids, while the rest is moisture [33]. The food waste also contains certain micronutrients: calcium (Ca^{2+}), potassium (K^+), sodium (Na^+), magnesium (Mg^{2+}), iron (Fe^{3+}), manganese (Mn^{2+}), zinc (Zn^{2+}), phosphorus (P) and sulfur (S) [34]. With high carbohydrate and protein percentages, food waste can be hydrolyzed to obtain fermentable sugar and free amino nitrogen (FAN). Furthermore, with a controlled mineral salts concentration, it can serve as an excellent substrate for the microbial fermentation to produce value-added bio-based products such as enzymes, biochemical precursor molecules, biopolymers, biofuels etc. As per an estimate, for every 1 kg of organic fraction of municipal food waste (OFMSW) the composition is starch (586.3 g), cellulose (56.3 g), lipid (64.5 g), and protein (83 g), which can be theoretically converted to 364 g of ethanol or 383.2 L of methane in an ideal process [35].

The current article will review the advancements made in using the food waste as an alternative source for bioethanol production. The article is presented in a way that matches the most commonly used theme as sections for bioethanol production with any substrate starting with substrate (food waste), upstream processing (pretreatment), fermentation, downstream processing (in situ product separation) to obtain the finalized product. The sections will cover the recent work completed, challenges faced and how the challenges are addressed and what changes can be made to better address those challenges.

2. Substrate

2.1. Food Loss and Waste (FLW)

The waste produced in the food value chain from production to consumption is regarded as the food value chain waste or food waste. There has been a difference of opinion among researchers to categorize the food loss and food waste. The food loss has been characterized as the food products that do not reach the customers due to issues in the primary production, handling, storage, transportation, processing and product import [36]. It can comprise the crop, livestock and fish human-edible commodity waste that, directly or indirectly, completely exits the post-harvest/slaughter/catch supply chain by being discarded, incinerated or otherwise disposed of, and does not re-enter in any other utilization (such as animal feed, industrial use, etc.), up to, and excluding, the retail level [37]. On the other hand, food waste is characterized as the waste that occurs from retail to the final consumption/demand stages and comprises mainly food that is good for human consumption [38]. It can include food waste generated from the wholesale, retail, household, commercial operations, and municipal food waste. A general consensus has not been established in defining food waste vs. food loss [39]. This discrepancy exists even among the agencies; the Food Waste Index by the UNEP includes non-edible parts but the loss estimated by FAO does not [36]. Hence, considering the totality of losses and waste along the food value chain and an ease of inclusion of food loss and waste as substrate for the bioethanol production, Food Loss and Waste (FLW) will be used throughout the article. The FLW does not includes the crops lost pre-harvest due to pests, diseases and being left in the field, poor harvesting, sharp price drops or food excluded due to lack of adequate agricultural inputs, strict hygienic and sanitary requirements, substandard product, and labor availability [38,40]. The food waste has also been quantified in terms of the weight, calorific value, and nutritional value, but the article will include the FLW categorized as per the value chain that can be used as a substrate for bioethanol production [40].

2.2. FLW Production

A successful bioprocessing operation requires a continuous economical supply of the substrate to ensure that the operations can be run smoothly and hence warrants an understanding of the substrate supply chain, substrate characteristics, substrate variations due to different vendors, seasons, transportation time, storage etc. With FLW being produced at different levels of the food value chain, an understanding for the FLW amount generated at each step helps to estimate how the continuous economical substrate requirement can be met. Figure 2 shows the percentage contribution of different categories of FLW in different regions.

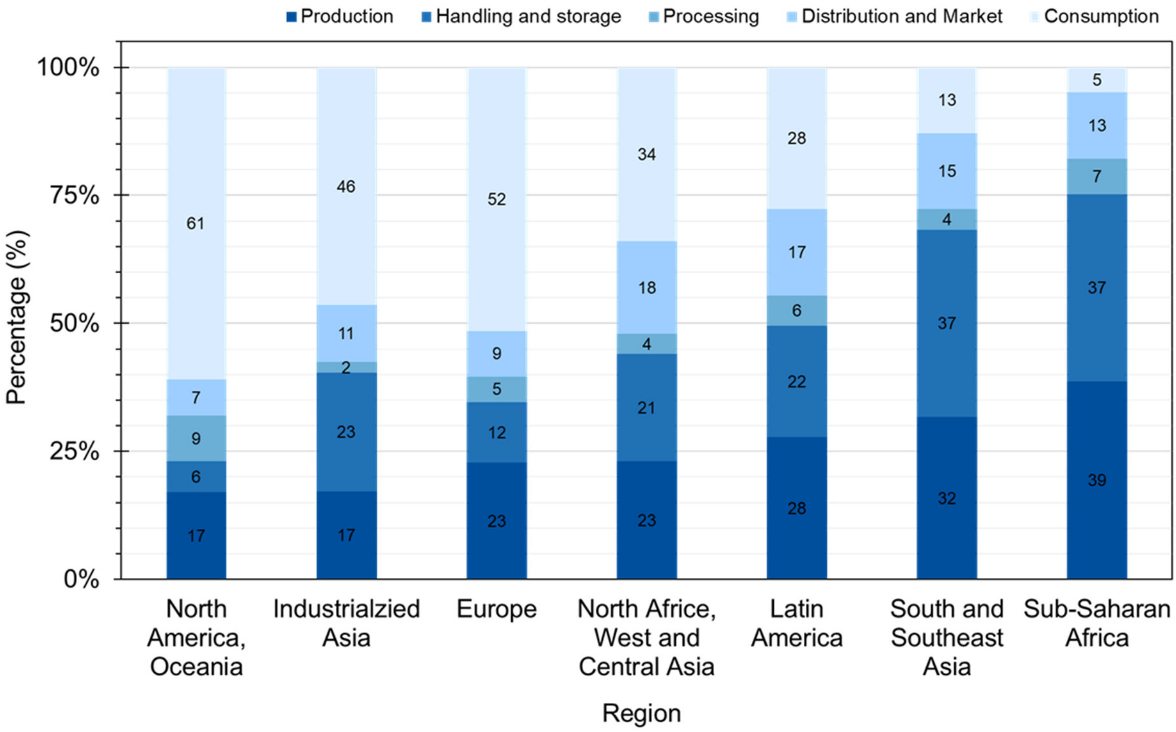

Figure 2. The percentage of food loss or waste by region and stage in the food value chain in 2009 [Source WRI analysis based on FAO. 2011 [41].

The FLW in the primary production step includes the production, pre-slaughter, harvesting, post-harvesting and post-slaughter items, the qualitative, and quantitative characteristics of which are unsuitable for sale as human food/animal feed or donation [42,43]. The FAO estimates that 30–40% of total production can be lost before it reaches the market [22,44]. Around 20% of the fruits and vegetables produced in North America are lost at the farm level [45]. A study conducted in California USA found that 57% of watermelon, 52% of cabbage, 44% of strawberries, 39% of kale and 13% of romaine hearts were lost during harvest [46]. In Nordic countries, 26% of the carrot crop and 15% of the onion crop was edible but unutilized [47]. The amount of FLW from vegetables, meat production, and tillage toward primary FLW in Ireland was 1.23, 0.41 and 0.13 million metric tons (MMT), respectively, with pests, disease, injuries, and production stress; unharvestable; and un-saleable contributing 37%, 24%, and 21%, respectively, toward the total primary FLW tonnage [48]. Overall, 49% of cattle, 47% of sheep and lamb, 44% of pigs, and 37% of broilers live weight is considered non-edible [49]. While transporting the primary produce, 14% of the world's food is lost [23]. The developing, and the underdeveloped countries are affected most with this where due to premature harvesting, an absence of adequate storage, poor infrastructure, inadequate marketing, and inadequate storage facilities, the primary product is rendered unfit for human consumption or to be used as animal feed [50]. In Karokh, Afghanistan, 50% of the tomatoes produced were lost due to rough shipping and handling during transportation [41]. The dairy products, meats, and fish products are more sensitive to deterioration compared to agricultural products and need to be kept in a chilled or frozen state along the entire supply chain to prevent pathogen growth and product spoilage [51]. Around 55 MMT of milk is lost before it reaches the shelf for sale, and an annual fish loss by spoilage is estimated to be 10–12 MMT [52,53]. Once at the manufacturing and processing site, the primary produce is processed and prepared for end consumers. However, around 4.81 MMT of FLW was estimated to be generated at the manufacturing sites in 2016 with 93% of the food processing FLW being recycled for use as animal feed or composting, resulting in overall energy and economic loss [54]. The manufacturing and processing sites use a good amount of water for processing and thus generate a liquid phase FLW stream viz. whey from cheese, yogurt, and tofu production, bakery effluent from equipment washing, brewery effluent, oil mill effluent, soda industry effluent potato processing wastewater, and apple pomace sludge, in addition to the solid phase waste viz. tomato waste, apple pomace, inedible dough, waste bread, potato waste, soybean curd residue and grape pomace from wineries [34,55]. The dairy products and fruit processing, respectively, required 9000–18000 and 32,000 L/metric^3 during processing [34,56]. Similarly, a tofu manufacturing facility generates around 0.25 kg of tofu curd residue from one kg of soybeans rich in nitrogen but low in carbohydrates [57]. The liquid FLW stream from the beverage industry has approximately 10–12% (w/v) sugar content, and such a high sugar content can be directly used for inoculum preparation or directly for bioethanol production. [58]. The liquid FLW is also rich in nutrients and can be used for bioethanol production in a similar fashion as the solid FLW stream. A yearly consumption of 45 MMT tons of oranges generates 45–60% of the total fruits as waste [59]; tomato processing generates 40% (w/w of total tomatoes) comprising seeds (33%), skin (27%), and pulp (40%) [34], and the processing of 675.85 MMT of the paddy produced globally generated 136, 45.36, 40.8, 27.2 and 6.4 MMT, respectively, of rice husk, rice bran, broken, unripe and discolored rice [60].

FLW generated in the wholesale and retail sector is significant but lower when compared to FLW generated in the other categories. As per a survey by BSR food manufacturers, wholesalers, and retailers together disposed of a total of 4.1 billion pounds of FLW in the United States in 2011 (2.4 billion pounds in the manufacturing sector and 1.7 billion pounds in the retail and wholesale sectors) [61]. Analyzing the data collected in New South Wales, the EPA's Bin Trim program showed that a total of 24.6 MMT of FLW was generated in the retail sector. The food and vegetables retailers were the largest contributor (4.1 MMT) to the waste produced [62]. Potato and banana make up the majority of the vegetable and fruit waste, amounting to a total of 1.2 MMT. FLW from the household makes up for the majority of the FLW. Most of the food waste produced in the developed countries comes from the household food waste, whereas the low-income countries show a small share of food waste in households [63]. As the per capita GDP increases in a household, the per capita food waste in the household also increases [64]. The commercial FW sector includes food served outside the households, and it includes restaurants, canteens, schools, cafeterias, hospitals, care centers, military institutions, transport hubs, and in-flight catering, making it one of the biggest FW contributors in several countries, trailing the household FW. In Germany, it accounted for 17% of total FW, in Finland, it accounted for 20%, and it was 11–17% of the total FW in China [64]. The majority of the food waste is produced at the consumer level and is also one of the leading contributors to the municipal solid waste. Figure 3 shows the global estimates of FLW produced at the household level. The regions with a higher percentage of the household FLW make a good case for the countries to have a bioethanol production plant as a supply chain corridor that can be established to meet the continuous economic substrate demand for bioethanol production.

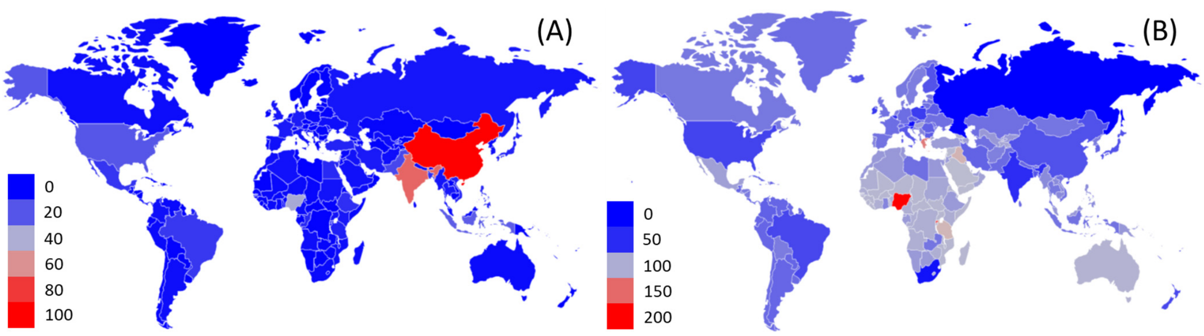

Figure 3. The estimates from different countries for (**A**) Household food waste estimate (MMT/year) and (**B**) Household food waste estimate (kg/capita/year). The countries with high estimates [Source: [36]].

The majority of the household FLW ends up being in the municipal solid waste. Figure 4 shows the proportionate contribution of food waste toward the total municipal solid waste of 265.53 MMT produced in the USA during the year 2018 and the respective energy generation from different components [65]. FLW is the major contributor to the energy generation by combustion of the municipal solid waste. Using it for bioethanol production can use this lost energy in a better way. This can be utilized as one of the sources for ensuring the continuous supply and procurement of FLW for bioethanol production.

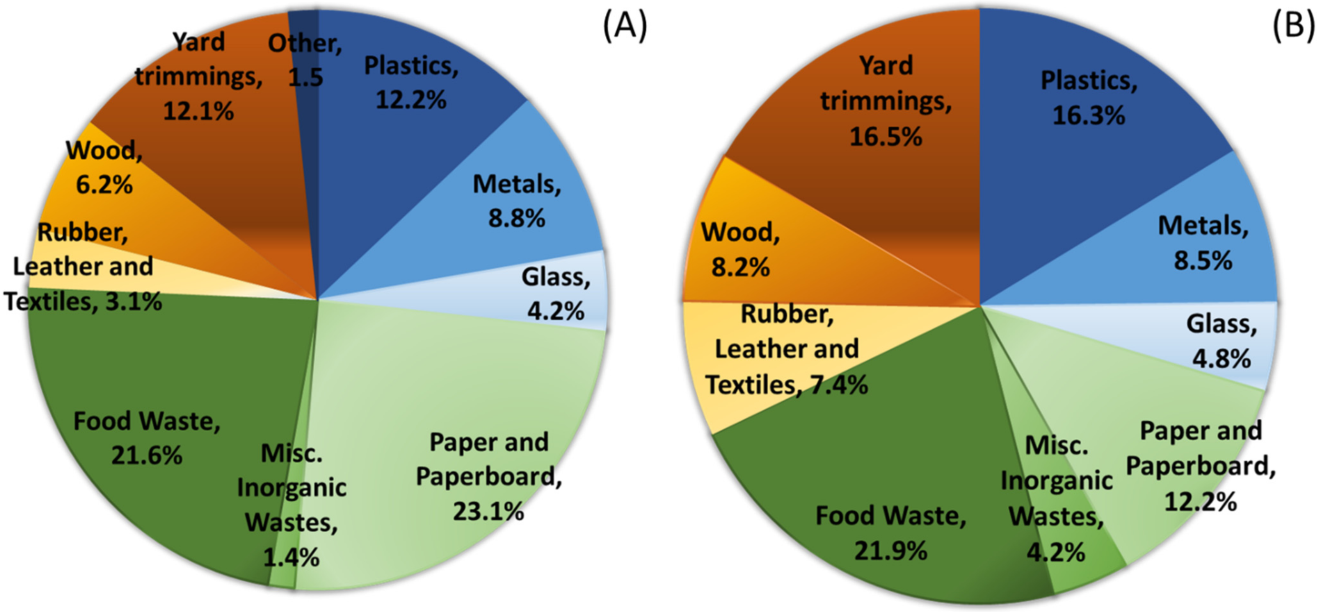

Figure 4. (**A**) The percentage distribution of USA MSW composition, 2018 (265.53 MM tons), and (**B**) The percentage distribution of energy recovery by combustion in U.S.A. (33.7 MM tons) [65].

2.3. Composition

FLW is compositionally rich in carbon (soluble sugars, reducing sugars, polymers and lignin), nitrogen (protein, peptides and amino acids), lipids (fatty acids, oil) and mineral salts (Mg, Ca, Na, K, etc.) and can be utilized to produce bioethanol in a proportionate method providing a sustainable measure to recover and utilize the energy in these. The agricultural (vegetables, fruits, by-products)-based FLW is rich in cellulose, hemicellulose, pectin, starch, lignin, minerals, vitamins, and bioactive compounds, whereas the livestock, dairy and seafood portion (blood, feathers, tallows, deceased and dead animals but excludes excreta) is usually rich in protein, carbohydrates, fats and calcium carbonate [47]. Several agricultural waste products such as corn stover, plant stem, leaves and roots, and poor agricultural product have been used for bioethanol production [66–68]. The animal by-products, slaughterhouse waste and wastewater rich in protein is generated in the slaughterhouses [69]. A portion of slaughterhouse waste is processed and recycled in process commonly known as rendering to produce raw materials viz. meat and bone meal (MBM), meat meal, poultry meal, hydrolyzed father meal, blood meal, fish meal for use in animal and pet feed due to high nitrogen content. For example, chicken feather contains 91% protein, blood meal contains 80–90% protein, and spent hens contain 25% crude protein on dry weight basis, making them a high protein, peptide, and nitrogen source favorable for application in bioprocess development. In 2004, the USA and Canada produced a combined total of 2.4 MMT of MBM [70]. The juice and beverage waste can also be used to dilute the media replacing the water requirement in the bioprocess. The watermelon juice waste comprising fermentable sugars (7–10% w/v) and free amino acids (15–35 µmol/mL) was used as a diluent, nitrogen source and carbon source in addition to molasses used for bioethanol production [71]. This high-protein ingredient can be used as a substitute for the costly nitrogen sources used in the bioprocesses. The requirement will be to choose components that can address the different requirements of the fermenting microbes. Table 1 shows the composition of the various FLW items at different stages of the food supply chain and can be an excellent source of energy and nitrogen for bioethanol production.

Table 1. The compositional profile of various waste products at different levels of food value chain (per 100 g).

Waste	Type and Food Value Chain	Moisture (%)	Carbohydrate (%)	Protein (%)	Fat (%)	Mineral (%)	Fiber (%)	Reference
Apple (Whole)	Food loss: Primary production loss	86 ± 4.72	10.39 ± 1.67	0.77 ± 0.23	0.126 ± 0.04	0.32 ± 0.06	2.4 ± 0.36	[72–75]
Apple pomace	Food waste: Food processing waste	79.2 ± 3.17	1.3 ± 0.56	1.42 ± 0.54	0.87 ± 0.35	0.52 ± 0.15	17.02 ± 2.62	[72,76,77]
Banana (Whole)	Food loss: Primary production loss	78.1 ± 4.14	16.07 ± 2.32	1.14 ± 0.24	0.4 ± 0.13	1.3 ± 0.64	3.1 ± 0.86	[72,78]
Banana peels	Food waste: Food processing waste	84.6 ± 4.23	4.62 ± 0.83	1.09 ± 0.032	1.79 ± 0.041	1.85 ± 0.028	6.05 ± 0.13	[79,80]
Carrot	Food loss: Food Processing Waste, Transport, Storage	89.3 ± 1.4	6.17 ± 1.62	0.96 ± 0.34	0.17 ± 0.08	0.79 ± 0.33	3.2 ± 0.18	[81,82]
Carrot pomace	Food loss: Primary food production loss	4.61 ± 0.21	24.73 ± 1.22	10.06 ± 0.18	1.75 ± 0.01	7.29 ± 0.32	45.12 ± 1.08	[83]
Orange waste	Food loss: Primary food production loss	4.15 ± 0.32	22.28 ± 0.93	8.72 ± 0.36	1.57 ± 0.02	10.03 ± 0.54	41.17 ± 1.28	[83]
Pomegranate husk	Food waste: Food processing	5.5 ± 1.25	4.34 ± 0.01	1.26 ± 0.17	3.57 ± 0.38	3.59 ± 0.08	17.75 ± 1.61	[84]
Pomegranate seed	Food waste: Food processing	25.66 ± 0.09	4.67 ± 0.02	10.42 ± 2.61	10.33 ± 0.17	3.62 ± 0.13	12.12 ± 2.10	[84]
Bread waste	Food loss and waste: Consumer, Wholesale, Retail, Transport, Storage	24.3 ± 0.8	58.6 ± 14.4	11 ± 2.1	1.8 ± 0.4	1.7 ± 0.5	3.2 ± 1.29	[85,86]
Cake waste	Food loss: Consume and Retail	45 ± 6.32	36.7 ± 7.26	9.35 ± 2.78	10.45 ± 2.36	0.88 ± 0.023	-	[87,88]
Green Pea peels	Food loss: Primary food production loss	4.28 ± 0.27	19.82 ± 1.36	13.27 ± 0.51	1.34 ± 0.03	7.18 ± 0.34	51.48 ± 1.34	[83]
Sugar beet pulp	Food Waste: Food processing	75.7 ± 2.27	1.51 ± 0.54	2.13 ± 0.17	0.12 ± 0.05	2.03 ± 0.71	18.51 ± 2.12	[89]
Maize extruded	Food loss: Food processing	13.7 ± 2.3	63.8 ± 10.56	7.6 ± 2.31	3.6 ± 1.21	1.25 ± 0.80	10.7 ± 1.6	[72,90]
Rice paddy	Food loss: Primary production waste	12 ± 0.25	55.6 ± 1.4	7.5 ± 1.4	2.2 ± 0.18	5.2 ± 1.23	17.52 ± 5.54	[90]
Rice bran	Food waste: Food processing waste	10 ± 1.3	41.22 ± 8.2	12.78 ± 1.44	11.88 ± 1.6	6.21 ± 0.8	15.3 ± 1.3	[72]
Rice straw	Food waste: Primary production waste	8.2 ± 0.12	-	4.14 ± 1.02	1.3 ± 0.28	16.8 ± 2.97	64.12 ± 3.9	[91,92]
Rice, polished, broken	Food loss and waste: Food processing	12.4 ± 1.1	75.4 ± 3.85	8.1 ± 1.6	1.1 ± 0.2	1.1 ± 0.13	2.1 ± 1.57	[90,93]
Soybean extruded	Food waste: Food processing	10.5 ± 0.2	12.9 ± 2.23	36 ± 1.16	18.4 ± 1.42	5.18 ± 0.45	17.06 ± 2.14	[90,94]
Soybean hulls	Food waste: Food processing	10.9 ± 0.89	6.05 ± 4.27	11.67 ± 1.6	1.96 ± 0.8	4.63 ± 0.27	65.2 ± 4.54	[95,96]

Table 1. *Cont.*

Waste	Type and Food Value Chain	Moisture (%)	Carbohydrate (%)	Protein (%)	Fat (%)	Mineral (%)	Fiber (%)	Reference
Sugarcane bagasse	Food waste: Food processing	54 ± 5.67	-	0.97 ± 0.16	0.32 ± 0.11	3.19 ± 1.08	41.52 ± 5.51	[97]
Tomato pomace	Food waste: Food processing waste	76.74 ± 4.48	7.56 ± 1.67	4.48 ± 0.63	2.28 ± 1.64	1.32 ± 0.63	8.16 ± 1.38	[98,99]
Wheat Bran	Food waste: Food processing waste	87 ± 1.1	4 ± 0.68	2.94 ± 0.17	0.67 ± 0.11	0.95 ± 0.09	4.44 ± 0.82	[100,101]
Wheat (whole)	Food loss: Primary production loss	87 ± 1.3	11.75 ± 0.5	2.14 ± 0.22	0.3 ± 0.05	0.31 ± 0.03	1.24 ± 0.03	[101,102]
Kitchen garbage	Food waste: Consumer	82.78	10.8	2.68	3.11		0.39	[103]
Whey	Food waste: Food Processing	3.0 ± 0.04	71.93 ± 2.71	11.64 ± 0.87	1.26 ± 0.5	7.95 ± 0.5	-	[104]
Bakery Waste	Food waste: Food Processing, Consumer, Transport, Storage	9.3 ± 0.35	70.8 ± 13.42	11.25 ± 1.81	5.0 ± 3.36	2.54 ± 0.82	1.1 ± 0.035	[105]
Cafeteria food waste	Food waste: Consumer	71.6 ± 1.86	15.94 ± 1.03	2.5 ± 0.23	1.87 ± 0.20	1.80 ± 0.26	6.29 ± 1.56	[106]

2.4. Transportation and Storage

A continuous abundant substrate availability and the lower transportation cost of the substrate are essential to determine the production site. As per an estimate, the cost of transporting FLW to the production site by road using a truck was calculated at around 0.14 USD/tkm [107]. Another study estimated a price expense of 100 USD/hour for liquid waste transportation and 2.5 USD/km for the transportation of solid waste [108]. Using a base case of 52 operational weeks in a year and 12 trips for the transportation of liquid waste and with each trip of 4 h (average), it would amount to a cost of 0.25 million USD/year. On the other hand, for solid waste with a hauling distance of 100 km, it would cost 0.26 million USD/year. These base case estimates are contingent upon the key variables (1) time to transport, (2) number of trips, (3) amount of waste transported, (4) distance to transport and (5) operational time, and variations in the variables will result in different estimates. New York, Mexico City, and Tokyo are the three top most trash producing cities globally with 33 MMT, 12.2 MMT and 11.9 MMT annual trash production, respectively [109]. The closer proximity of the biorefinery to sites (cities) which produce a large quantity of FLW will reduce the overall transportation cost. Obtaining food waste in a timely manner is one of the crucial steps in the bioethanol production process. The high-water activity, nutrients and favorable growth conditions allow the growth of several bacteria and fungi viz. *Pseudomonas*, *Shwenella putrefaciens*, *Brochothrix thermospachata*, lactic acid bacteria, *Mucor*, *Aspergillus* etc. [110] that compete for the available nutrients with the fermenting organisms. To prevent compositional changes and pathogen growth, Bibra and coworkers [106] stored the food waste at 4 °C before use for bioethanol production. In another work, [111] dried the household food waste for bioethanol production. Drying helps in preventing pathogenic growth but reduces the active surface area available for fermentation. Some authors used biological treatment to prolong the longevity of food waste in storage. Ref. [112] used LAB on the food waste to prevent possible bacterial contamination before bioethanol production. An ethanol concentration of 45 g/L was obtained when the food waste was inoculated 0.5% (*v*/*v*) *Lactobacillus plantarum* for 48 h. An energy-intensive step might be required for storing or processing the food waste collected to mitigate pathogenic growth and prevent compositional changes.

3. Upstream Processing

FLW is a complex substrate where complexity is increased by inherent composition and requires treatment to obtain the sugars for the bioethanol production. The treatment can relax the conformational stiffness in the hydrolysis step, and it makes it easier to obtain the sugars for fermentation in the saccharification step, reducing the process retention times and increasing product conversion efficiency [113].

Separation and Pretreatment

The FLW is obtained in plastic bags, packaging cartons, cans, etc. that needs to be removed to access the food waste for further processing [114]. The sorting of food waste at the production site can help in time and energy reduction required to segregate the food waste because as the FLW moves up the food value chain, the ease of separating different components reduces, while the probability of its deterioration by physical, chemical and biological factors increases. Figure 5 shows the loss percentage of FLW across different food value chain stages and decreasing easiness for waste separation complexity from source as it moves from pre-harvest to the whole sale supply chain. As the difficulty of separating the waste increases, the cost of obtaining reducing sugars will also increase. It is because of this reason that food waste from the landfill sites is preferred for anaerobic digestion or steam generation.

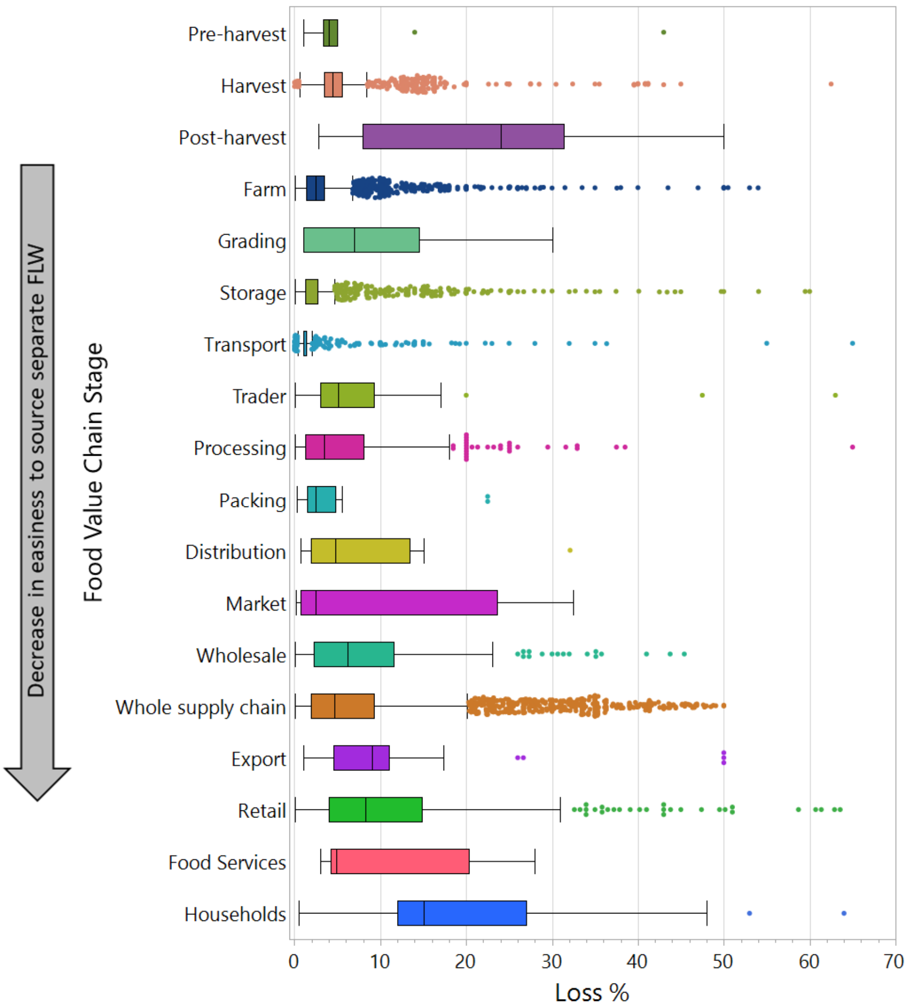

Figure 5. The global loss percentage of FLW across different stages in the food value chain from 2000 to 2022 (Adapted with permission from [115]) and decrease in easiness to separate waste in the food value chain.

The first step in the upstream processing is to separate the non-edible components from the FLW [116]. In addition to the packaging material, FLW can also have metal components that need to be separated from a safety and operational perspective. The FLW is processed in a hammermill that shreds and chops the material and aids in the separation of the packaging materials. The shredding and chopping by hammermill works as a physical pretreatment method which can provide enhanced surface area by providing optimized particle size [117]. Naidu et al. (2007) reported a 12.6% (*v*/*v*) ethanol production with a 0.5 mm size of corn compared to 1.62% (*v*/*v*) with 5 mm sized corn particles [118]. The milling of dried food waste reduced the household FLW size to 3 mm particles [111]. The food waste collected from a local supermarket in Japan rich in carbohydrates (rice, bread, pasta, noodles etc.), and protein (fish, beef, pork, chicken etc.) was chopped into small pieces using a food processor. The chopping increased the accessible surface area for saccharification and produced 99.8 g/L ethanol with *Zygomonas mobilis* ZMA7-2 [18]. A sugar yield equivalent to 94.8% of that obtained by enzymatic conversion was obtained after the extrusion of soybean hulls with a screw speed of 350 rpm, temperature of 80 °C, and in-barrel moisture content of 40% (*w*/*w*) [119].

In addition to the use of physical pretreatment for separation and size reduction, different chemicals viz. sulfuric acid, nitric acid, phosphoric acid, hydrochloric acid, H_2O_2, organosolvs, ammonia, hot water, enzymes, microorganisms etc. have been used for the pretreatment of FLW [120]. Chemical and biological processes individually or in combination had been used widely and been the method of choice for obtaining the fermentable sugars. The dilute acid treatment followed by enzymatic treatment is the most sought and successful pretreatment method with comparatively less inhibitor formation than in concentrate acid pretreatment [121]. The dilute acid treatment changes the structural conformation, depending on the parameters (temperature, time, type of acid, and concentration), and it also increased the surface area accessibility of the substrate to aid better enzymatic hydrolysis and saccharification [122]. Kim and coworkers (2018) optimized and scaled up the dilute acid fractionation of liquid and solid portions of the dried food waste, using sulfuric acid 0%,0.4 and 0.8% (*v*/*v*) at a temperature of 130, 160 and 190 °C for 1, 64.5 and 128 min [123]. The maximum glucose concentration (26.4 g/L) was obtained from food waste treated with 0.37% (*v*/*v*) H_2SO_4 at 149.8 °C for 123.6 min. Mahmoodi and coworkers used dilute H_2SO_4 pretreatment followed by treatment with Cellic Ctec 2 to pretreat the food waste from MSW to produce hydrolysate with a sugar concentration of 25 g/L [35]. The further fermentation of the hydrolysate with *Mucor indicus* gave an ethanol titer of 20 g/L. Similarly, a higher sugar content was obtained after dilute acid treatment (HCL-33.7 g/L, and H_2SO_4-40.5 g/L) than with the hydrothermal treatment (27.6 g/L) carried at T = 90 °C before proceeding with the enzymatic hydrolysis [124]. Furthermore, enzyme treatment post-acid treatment gave a sugar yield of 103.4 g/L compared to 50.5 g/L and 60.3 g/L obtained with acid and enzymatic hydrolysis alone, respectively. The conversion efficiency improved from individual, 42.4% (acid) and 50.6% (enzymatic) to 86.8% in sequential hydrolysis. The food waste used consisting of mashed potatoes, sweet corn and white bread used by Huang and coworkers was subjected to pulverization, 10 N sulfuric acid and α-amylase and glucoamylase ($\geq$570 granular starch hydrolyzing units (GHSU) and acid protease (2000 spectrophotometer acid protease units (SAPU) for increased sugar production [125]. Here, 200 g/L of sugar obtained gave an ethanol yield of 144 g/L. A material balance estimate analysis on the pretreatment of 3.7 metric tonnes of FLW comprising beverage waste (73%), bakery waste (6.74%) and carbohydrate-rich waste (20.22%) at a solid loading of 37.5% (*w*/*w*) by sucrase (Novozyme, 0.025% *w*/*v*) and glucoamylase (Novozymes, 1% *w*/*v*) at pH 5.0 and temperature of 50 °C showed that 3.17 metric tonnes of sugar-rich hydrolysate (glucose (228.1 g/L) and fructose (55.7 g/L)) can be obtained with an overall conversion yield of 0.17 g sugars/g of mixed waste in 12 h [126]. The ability to obtain such a high concentration of simple sugars that can be directly used for fermentation makes the FLW lucrative. The direct use of microorganisms producing hydrolytic enzymes has also been carried out to pretreat FLW, but it has been shown to cause sugar reduction also due to use by the microorganism-producing enzymes [111]. *Hymenobacter* sp. CKS3 was used to produce amylolytic enzymes to hydrolyze the bread waste to produce sugars (19.86 g/L) and then produce ethanol (17.3 g/L) with *Saccharomyces cerevisiae* [127]. This approach is more beneficial when using a consolidated bioprocess compared to the separate hydrolytic or simultaneous saccharification bioprocess.

The pretreatment costs can contribute toward a significant portion of the minimum ethanol selling price, and that is why pretreatment sometimes has been coined as the necessary evil in the bioprocess development. As per one study, the pretreatment of the lignocellulosic biomass by enzymes can cost 17% of the minimal ethanol selling price of 568 USD/m^{-3} treatment [128]. A well-planned strategy for FLW pretreatment is very important to make the overall process economical. The proportion of FLW components viz. proteins, lipids, and lignocellulosic can aid in the decision-making process for pretreatment. The different items contributing to FLW have different compositions, but waste from the same processing facility can also have different composition and may require a different pretreatment strategy. Rice husk (38.6% cellulose, 15.9% hemicellulose, 16% lignin, and only 7% starch) produced in the rice-milling facility had a different composition than the other products: rice bran (4.6% cellulose, 8.4% hemicellulose, 2.8 % lignin, and 28.5% starch), unripe (1.8% cellulose, 3.7% hemicellulose, 0% lignin, and only 68.6% starch), broken (0.2% cellulose, 0.5% hemicellulose, 0% lignin, and 77.7% starch), and discolored rice (0.1% cellulose, 0.9% hemicellulose, 0% lignin, and only 84.6% starch) [60]. This necessitates difference pretreatment strategies for the different components. The rice bran required treatment with H_2O_2 at 55 °C for 24 h to remove the structural hindrances in order to obtain fermentable sugars followed by saccharification with cellulase enzyme, while the other rice milling waste products did not require treatment with the H_2O_2. The composition and contribution of the fiber content in the FLW can also influence the type of enzymes required and the pretreatment costs. The materials with higher fiber content, such as agricultural refuse, agricultural processing waste, and higher cellulose and hemicellulose content will require more costly pretreatment methods compared to materials with comparatively higher pectin content in the fiber portion viz. apple pomace, fruit waste, etc. The stringent pretreatment conditions for the materials with higher fiber content can also result in lower sugar yields. The grape pomace rich in cellulose, hemicellulose, and pectin when enzymatically treated with cellulase, hemicellulases, and pectinase gave 14% more sugars compared to that obtained in acid hydrolysis with 12 M H_2SO_4 [129]. However, opposite to it, the sequential treatment of sugarcane bagasse with NaOH, HCl, and liquid hot water followed by cellulase gave higher glucan and xylan conversion. Then, 77.3% of the sugars were recovered from sugarcane bagasse after 90% of the lignin was removed in the dilute alkali pretreatment with NaOH [130]. Increasing the relative proportion of the starch rich FLW can help to reduce the overall enzyme cost due to the reduction in overall enzymes required for obtaining sugars from FLW.

After pretreatment, the liquid with sugar residues can be either concentrated or used directly for the fermentation. Bioethanol is a commodity product that falls under high-volume low-value products in the bioproducts category. Thus, a profitable bioethanol venture requires the production of high volumes of bioethanol continuously. For such high-volume products, it is quintessential to concentrate the sugar so that the volume profile can be controlled. The technoeconomic analysis for obtaining sugar syrup started with FLW comprising of food waste (10 MT/h) and beverage waste (14 MT/h) at a solid concentration of 40–70% (w/w) and gave 0.24 MT sugars/MT of the waste used [131]. The FLW was treated with 1% (w/v) glucoamylase and 0.025% (w/v) of sucrase at 50 °C and pH 5.0. The impurities such as preservatives, colorants, caffeine, ions and soluble proteins in the hydrolysate broth were removed using column chromatography, and the hydrolysate obtained was treated with glucose isomerase to obtain 1:1 mixture of glucose and fructose. The two sugars were separated using a simulated moving bed system [131,132]. The clarification of the sugar syrup in the upstream processing helps to obtain a clean stream for downstream processing; however, the overall process economics should drive the decision.

4. Fermentation

4.1. Microorganism

The fermentation bioprocess for bioethanol production involves the biotransformation of a substrate rich in carbon and nitrogen to ethanol and other by-products viz. glycerol, lactic acid, acetic acid based on which fermentative microorganism is used. Microorganisms: *Saccharomyces cerevisiae*, the most common yeast used for ethanol production, had also been extensively used with FLW as it (1) has high productivity (2) can grow under aerobic and anaerobic conditions to aid in biomass generation and ethanol production, (3) achieve near theoretical maximum bioethanol yield with glucose, i.e., 0.51 g ethanol/g sugar at high production rates [20,133,134]. After pretreatment, the use of *Saccharomyces cerevisiae* is very prevalent for bioethanol bioprocess development, and it is equally proportionate between FLW rich in starch or in lignocellulosic material due to its well-established use, greater understanding of the physiology and metabolic events and commercial success associated with it. *Saccharomyces cerevisiae* strain KL17 fermented the acid hydrolyzed and enzymatically treated bread waste and produced 106.9 and 114.9 g/L of ethanol, respectively, with an ethanol yield of 0.47 g/g and 0.49 g/g per unit substrate, respectively [135]. When used in the fermentation of organosolv pretreated rubberwood waste, *Saccharomyces cerevisiae* produced 0.14 g/g of substrate ethanol [136]. The simulated modeling results for life cycle analysis by Ebner and coworkers reported an ethanol yield of 295 L/dry ton of retail food waste fermented by *Saccharomyces cerevisiae* [137]. Although the use of *Saccharomyces cerevisiae* is very widespread, its inability to use different sugars and limited capability to produce hydrolytic enzymes restrict its ability for use in a robust bioprocess with ability to intake a wide variability in FLW and reduce the pretreatment and overall cost.

Zymomonas mobilis, a Gram-negative ethanol-producing bacteria is another organism that has been researched extensively for bioethanol production owing to the (i) anaerobic growth ability, (ii) high sugar and ethanol tolerance and (iii) metabolize sugar via the Entner–Doudoroff (ED) pathway [138]. The Entner–Doudoroff (ED) pathway is favorable for ethanol production as less ATP and less biomass is produced with more carbon sources channeled to ethanol, resulting in high ethanol yield and a higher glucose metabolic flux three- to fivefold that of *Saccharomyces cerevisiae* (Bai et al., 2008; Wirawan et al., 2012). An acid-tolerant *Zymomonas. mobilis* strain ZMA7-2 used with the food waste hydrolysate produced 99.8 g/L of ethanol [18]. In another study, *Zymomonas mobilis* 10,225 produced 53.20 g/L ethanol during fermentation of kitchen waste post-enzymatic treatment [103]. Apart from these two commonly employed organisms, *Mucor indicus* (*M. indicus*), a Zygomycetes fungi, had also been employed for ethanol production due to its higher ethanol tolerance than *S. cerevisiae.* Using *M. indicus*, Mahmoodi and coworkers (2017) reported a yield of 194 g/kg food waste [35], whereas Matsakas and coworkers obtained 107.58 g/kg food waste with *M. indicus* [139]. Another yeast strain, *Issatchenkia orientalis,* was used by Kim and coworkers to produce ethanol using the dilute acid-treated food waste due to its ability to carry out fermentation at pH 3.0 [123]. *Issatchenkia* has the ability to withstand lower pH, which helps in ethanol (11.1 g/L) production pH 3.0. Table 2 shows the ethanol production with different FLW and parameters used in the bioprocess.

Table 2. The bioethanol production with different food waste including different parameters used during ethanol production in each study.

Substrate, and Amount of Substrate [1]	Pretreatment	Organism	Fermentation Conditions	Fermentation Type	Bioprocess Type	Ethanol Produced	Yield (g/g) [7]	Productivity [8]	Reference
Food waste (200 g/L)	None	*Geobacillus thermoglucosidasius* and *Thermoanaerobacter ethanolicus*	T = 60 °C pH = 6.5 Agitation speed = 100 rpm Inoculum = 5% (*v*/*v*)	Fed-Batch, submerged with media components and inoculum addition at intervals	Consolidated bioprocessing [2]	18.1 g/L	0.1 g ethanol/g food waste	0.15 g/L/h	[106]
Potato peel waste (40 g/L)	None	*Wickerhamia* sp. strain SD1 (wild)	T = 30 °C pH = 7.0 Agitation speed = 300 rpm Inoculum = 2% (*v*/*v*)	Batch, submerged	Consolidated bioprocessing	21.7 g/L	0.54 g ethanol/g potato peel waste	0.23 g/L/h	[140]
Dairy waste (80 g/L lactose)	None	*Lactococcus lactis* subsp. *cremoris* strain MG1363 (Recombinant)	T = 30 °C	Fed-Batch (500 g/L lactose feed to at lactose 10 g/L to achieve 20 g/L), submerged	Fermentation	30.6 g/L	0.38 g ethanol/g lactose	0.77 g/L/h	[141]
Household food waste (25 g/L)	None	*Saccharomyces cerevisiae*	T = 30 °C	Batch, submerged	Consolidated bioprocessing	6 g/L	0.24 g ethanol/g household food waste	0.28 g/L/h	[111]
Bread waste (613 g/L)	Acid hydrolyzed (HCl 2% *v/v* and 20% *w/v* solid autoclaved at 121 °C for 15 min)	*Saccharomyces cerevisiae* strain KL17	T = 30 °C pH = 6.0 Agitation speed = 200 rpm Inoculum = 2% (*v*/*v*)	Fed-Batch (glucose 400 g/L feed to maintain concentration 20 g/L)	Separate Hydrolysis and Fermentation [3]	106.9 g/L	0.17 g ethanol/g bread waste	3.0 g/L/h	[135]
Bread waste (613 g/L)	Enzymatic treatment (Autoclaved at 121 °C for 15 min at pH 4.3, Dextrozyme-0.06% (*w*/*w*) loading at 60 °C and pH4.3)	*Saccharomyces cerevisiae* strain KL17	T = 30 °C pH = 6.0 Agitation speed = 200 rpm Inoculum = 2% (*v*/*v*)	Fed-Batch (glucose 400 g/L feed to maintain concentration 20 g/L)	Separate Hydrolysis and Fermentation	114.9 g/L	0.2 g ethanol/g bread waste	3.2 g/L/h	[135]
Grind waste cake (100 g/L)	Enzymatic (α-amylase-0.08% (*v*/*w*) at 95 °C, 200 rpm for 1.33 h)	*Saccharomyces cerevisiae*	T = 30 °C pH = NV* Agitation speed = 400 rpm Inoculum = 2% (*v*/*v*)	Batch, submerged	Separate Hydrolysis and Fermentation	46.6 g/L	1.12 g ethanol/g dry cake	1.17 g/L/h	[87]

Table 2. *Cont.*

Substrate, and Amount of Substrate [1]	Pretreatment	Organism	Fermentation Conditions	Fermentation Type	Bioprocess Type	Ethanol Produced	Yield (g/g) [7]	Productivity [8]	Reference
Food waste (330 g/L)	Screw pressed and dried using steam boiler at 150 °C Dilute acid treatment (H_2SO_4 0.4% *w/v* at 160 °C for 64.5 min)	*Issatchenkia orientalis*	T = 30 °C pH = 3.0 Agitation speed = 200 rpm Inoculum = 5% (*v*/*v*)	Batch, submerged	Separate Hydrolysis and Fermentation	11.1 g/L	0.04 g ethanol/g food waste	1.45 g/L/h	[123]
Damaged corn grains (140 g/L)	Crushed to powder and enzymatic pretreatment (Amylase-for 1 h)	*Saccharomyces cerevisiae* MTCC 170 (wild)	T = 31 °C Ph = 5.6 Agitation speed = 150 rpm Inoculum = 1 × 10^9 cells/mL	Batch, submerged	Simultaneous Hydrolysis and Fermentation	42.4 g/L	0.32 g ethanol/g damaged corn grains	0.88 g/L/h	[67]
Organic fraction of municipal solid waste (233 g/L)	Dilute acid pretreatment (H_2SO_4-1% *v/v* at 160 °C for 60 min), and Enzymatic treatment (Cellic Ctec2, and HTec 2–20 FPU/g dry substrate at 45 °C, 120 rpm for 72 h)	*Mucor indicus* CCUG 22,424 (wild)	T = 37 °C pH = 5.5 Agitation speed = 150 rpm Inoculum = 0.02% (*w*/*v*)	Batch, submerged	Separate Hydrolysis, Saccharification and Fermentation[4]	27.4 g/L	0.12 g ethanol/g waste	0.38 g/L/h	[35]
Organic fraction of municipal solid waste (233 g/L)	Dilute acid pretreatment (H_2SO_4-1% *v/v* at 160 °C for 60 min)	*Mucor indicus* CCUG 22,424 (wild)	T = 37 °C pH = 5.5 Agitation speed = 150 rpm Inoculum = 0.02% (*w*/*v*)	Batch, submerged	Separate Hydrolysis and Fermentation	19.1 g/L	0.082 g ethanol/g waste	0.27 g/L/h	[35]
Acid hydrolysate solid organic fraction of municipal solid waste (23.3 g/L)	Enzymatic treatment (Cellic Ctec2, and HTec 2–20 FPU/g dry substrate at 45 °C, 120 rpm for 72 h)	*Mucor indicus* CCUG 22,424 (wild)	T = 32 °C	Batch, submerged	Separate Saccharification and Fermentation [5]	9.5 g/L	0.41 g ethanol/g waste	0.13 g/L/h	[35]
Damage Rice grains (250 g/L)	Enzymatic (Amylase at 50 °C 100 rpm for 15 h)	*Paenibacillus chitinolyticus* strain CKS1 (wild)	T = 30 °C	Batch, submerged	Separate Saccharification and Fermentation	37 g/L	0.15 g ethanol/g damaged rice grains	0.62 g/L/h	[142]
Carob waste (50 g at 70% humidity)	Physical size reduction	*Sacchaaromyces cerevisiae* ATCC 7754 (wild)	T = 30 °C pH = 5.0 Inoculum = 3% (*v*/*v*)	Batch, solid state	Fermentation	-	0.15 g ethanol/g carob waste	0.0043 g/g/h	[143]

Table 2. *Cont.*

Substrate, and Amount of Substrate [1]	Pretreatment	Organism	Fermentation Conditions	Fermentation Type	Bioprocess Type	Ethanol Produced	Yield (g/g) [7]	Productivity [8]	Reference
Carob waste (150 g/L)	Aqueous extraction of milled carob waste at 3% (*w*/*w*) solid loading at 70 °C for 90 min)	*Saccharomyces cerevisiae* ATCC 7754 (wild)	T = 30 °C pH = 5.0 Agitation speed = 200 rpm Inoculum = 3% (*v*/*v*)	Batch, submerged	Separate Hydrolysis and Fermentation	26.1 g/L	0.45 g ethanol/g carob waste	1.84 g/L/h	[143]
Mixture of Rice milling by products (200 g/L)	Alkaline peroxide (7.5% (*v*/*v*) 55 °C for 24 h) and Enzymatic pretreatment (Cellic Ctec2-3% enzyme loading)	*Saccharomyces cerevisiae* strain M2 (recombinant#)	T = 30 °C pH = 5.5	Batch, submerged	Separate Hydrolysis, Saccharification and Fermentation	51.88 g/L	0.24 g ethanol/g rice milling by product	0.98 g/L/h	[60]
Food court waste hydrolysate (200 g/L)	Dilute acid pretreatment (H_2SO_4-1% *v/v* at 90 °C for 180 min) and enzymatic pretreatment (glucoamylase)	*Saccharomyces cerevisiae* (wild)	T = 30 °C pH = 6.5 Agitation speed = 120 rpm Inoculum = 10% (*v*/*v*)	Batch, submerged	Separate Hydrolysis, Saccharification and Fermentation	10.92 g/L	0.055 g ethanol/g food waste	0.46 g/L/h	[124]
Pie waste (30% *w*/*v*)	Enzyme pretreatment (α amylase, γ amylase, pectinase) 2.5 mg/g glucan	*Saccharomyces cerevisiae* ATCC 4124 (wild)	T = 30 °C pH = 5.5 Agitation speed= 150 rpm Inoculum= OD 2.0	Batch, Submerged	Simultaneous Saccharification and Fermentation [6]	103 g/L	0.34 g ethanol/g pie waste	2.14 g/L/h	[134]
Dairy waste (80 g/L lactose)	None	*Lactococcus lactis* subsp. *cremoris* strain MG1363 (recombinant)	T = 30 °C	Fed-Batch (500 g/L lactose feed to at lactose 10 g/L to achieve 20 g/L), submerged	Fermentation	30.6 g/L	0.38 g ethanol/g lactose	0.77 g/L/h	[141]
Supermarket food waste (2740 g/L)	Enzymatic pretreatment (glucoamylase-180 mg/kg food waste at 50 °C for 6 h),	*Zymomonas mobilis* strain ZMA7–2 (mutant*)	T = 30 °C pH = 5.6 RPM = 100 Inoculum = 10% (*v*/*v*)	Batch, submerged	Separate Saccharification and Fermentation	98.17 g/L	0.036 g ethanol/g waste	2.2 g/L/h	[18]

Table 2. *Cont.*

Substrate, and Amount of Substrate [1]	Pretreatment	Organism	Fermentation Conditions	Fermentation Type	Bioprocess Type	Ethanol Produced	Yield (g/g) [7]	Productivity [8]	Reference
Palm kernel cake hydrolysate (8.6 g/L)	Steam explosion (20% *w*/*v*) at 4.5 bar for 15 min, and enzymatic (mannase-17.9 U/g mannan and Cellic Ctec2-10.4 FPU/g glucan at 5% (*w*/*w*) solid loading at T = 50 °C, pH = 5. 250 rpm for 72 h)	*Geobacillus thermoglucosidasius (recombinant)*	T = 30 °C pH = 7.0 Agitation speed = 250 rpm Inoculum = 10% (*v*/*w*)	Batch, Submerged	Separate Saccharification and Fermentation	9.9 g/L	1.15 g ethanol/g waste hydrolysate	0.21 g/L/h	[144]
Household food waste (25 g/L)	Pretreatment by enzymatic treatment pH 5.5, enzyme loading 10 FPU/g waste, at 200 rpm, T = 60 °C for 8 h	*Saccharomyces cerevisiae*	T = 30 °C pH =5.5 Agitation speed = 100 rpm Inoculum = NV	Batch, submerged	Separate Hydrolysis, Saccharification and Fermentation	19.26 g/L	0.77 g ethanol/g household food waste	0.80 g/L/h	[111]
Organic fraction municipal solid waste	Fungal pretreatment for 24 h followed by particle reduction	*Zymomonas mobilis and Candida shehatae*	T = 35 °C pH = 5.0 Agitation speed = 180 rpm Inoculum = 15% (*v*/*v*)	Batch, Submerged	Separate saccharification and Fermentation	78.8 g/L	0.16 g ethanol/g food waste	1.09	[145]
Food waste, (2000 g/L)	Enzymatic pretreatment (amylase 10 U and 120 U glucoamylase/g fed food waste for at 55 °C for 4 h)	*Saccharomyces cerevisiae* sp. H058 (wild)	T = 30 °C pH = 5.0 Agitation speed = 100 rpm Inoculum = 2% (*v*/*v*)	Batch, Submerged	Separate Saccharification and Fermentation	90.72 g/L	0.045 g ethanol/g food waste	1.89 g/L/h	[20]
Apple pomace (800 g)	None	*Saccharomyces cerevisiae* Montrachet strain 522	T = 30 °C pH = NV RPM = NV	Batch, Solid state	Fermentation	-	0.044 g ethanol/g of apple pomace	1.48 g/g/h	[146]

1: The amount of food waste is based on wet basis (as is), as this is the form that is used for pricing the substrate and transportation. 2: Consolidated Bioprocessing—All the steps of pretreatment, hydrolysis, saccharification, and fermentation occur in same vessel under same conditions. 3: Separate Hydrolysis and Fermentation—Hydrolysis and fermentation occur in different vessels and conditions. 4: Separate Hydrolysis, Saccharification and Fermentation—Hydrolysis, saccharification and fermentation occur in different vessels and conditions. 5: Separate Saccharification and Fermentation- Saccharification and Fermentation. 6: Simultaneous Saccharification and Fermentation—Saccharification and Fermentation occur in the same vessel, at different conditions, no processing post saccharification. 7: Yield: g ethanol/g FLW (as is basis). 8: The productivity is based on the maximum production amount and time taken to achieve it.

Apart from monocultures, co-culture studies had also been conducted for bioethanol production using the food waste, as the most commonly employed monoculture fermentative microorganisms either sometimes lack the enzymatic machinery or the ability use different carbon sources simultaneously or completely at all. In such scenarios, the co-culture fermentation is advantageous, as it can alleviate the common issues viz. sugar production and utilization, enzyme production, and waste hydrolyzation and saccharification, faced by the ethanologenic strains and provide synergistic action of the metabolic pathways of all involved strains. Several studies have established the usefulness of the co-cultures. The co-culture of the hexose (*S. cerevisiae* strain CECT 1332) and pentose utilizing yeast (*P. stipites* strain CECT 1922) utilized 40% (*w*/*v*) waste hydrolysate and gave an ethanol yield of 45 g/L [147]. Similarly, the ethanol production using the potato waste as substrate when fermented by the co-culture of *Aspergillus niger* and *S. cerevisiae* gave an ethanol yield of 38 g/L [148]. *Aspergillus niger* produced the enzymes (glucoamylase) required and *Saccharomyces cerevisiae* carried out the fermentation to produce ethanol from the potato peel waste. A mixed culture of *Fusarium oxysporum* strain F3 and *Saccharomyces cerevisiae* by Prasoulas and coworkers produced 20.6 g/L of ethanol with acid pretreated and enzymatically hydrolyzed food waste [149]. *Fusarium oxysporum* produced the enzymes endoglucanase (211 U/g), β-glucosidase (0.088 U/g), cellobiohydrolase (3.9 U/g), xylanase (1216 U/g) and β-xylosidase (0.052 U/g) by growing on the wheat bran. This reduced the external enzyme requirement, but due to the absence of amylase enzymatic activity, its external addition (40 U/g FW) was completed to ensure complete hydrolysis of the food waste that increased the glucose content by 25% (*w*/*w*). Using a co-culture or a mixture of substrates can help to produce the required range of the substrates. However, using the co-cultures can also reduce the overall production, as the resources will be used by microorganisms in the co-cultures for cell growth and maintenance. This can be addressed by using the microorganisms in a sequential where the resources are used by only one organism at a time. Bibra and coworkers used *Geobacillus* and *Thermoanaerobacter* sps. in a sequential manner for the fermentation of food waste and obtained 18.2 g/L of ethanol [106].

The use of thermophilic fermentative microorganisms is also promising when using non-conventional substrates for bioethanol production as they provide (1) higher kinetic rates, (2) the ability to produce thermostable hydrolytic enzymes, (3) the ability to use different carbon sources, (4) reduced contamination risk, and (5) the ability to withstand toxic compounds due to rigid wall structure [150–153]. The ability to produce thermophilic hydrolytic enzymes and carry out fermentation makes the thermophiles an ideal candidate for consolidate bioprocessing. The sequential use of *Geobacillus* sp. DUSELR13 and *Geobacillus thermoglucosidasius* helped to produce the lignocellulose hydrolytic enzymes and produce ethanol with prairie cord grass and corn stover [151]. *Geobacillus* and *Thermoanaerobacter* sps. produced ethanol (18.2 g/L) from food waste at 60 °C without any pretreatment [106]. The majority of the sugars available from the food waste were utilized for bioethanol production, but the yield was lower compared to the other reported work. Table 3 shows the ethanol produced by thermophiles using FLW.

In addition to the use of wild-type microorganisms, bioprospecting, development, and the use of recombinant yeast and bacterial species can also aid to alleviate the challenges to use the FLW for bioethanol production. Several other yeast species such as *Candida*, *Scheffersomyces*, *Kluyveromyces*, *Pachysolen*, recombinant *Saccharomyces cerevisiae* sps. and bacterial species, capable of utilizing the various sugars for ethanol fermentation, have been used in the fermentation of food waste to ethanol [154–156]. Most commonly, recombinant work is carried out to increase the ability of the fermenting organisms to produce hydrolytic enzymes, increase the sugar uptake rate, improve the ability to co-metabolize different sugars, improve inhibitor tolerance, increase membrane fluidity, etc. The expression of cellulases on the cell surface of *Saccharomyces cerevisiae* NBRC1440 helped to hydrolyze a fraction of the rice straw hydrolysate unhydrolyzed by the commercial cellulases [157]. This increased the overall bioethanol produced from 34.5 to 42.2 g/L.

Table 3. Ethanol production by thermophiles using FLW.

Organism	Temperature	Substrate	Ethanol Produced	Advantages	Shortcomings	Reference
T. mathranii strain A3	65 °C	Food waste (20% *w*/*v*)	9.3 g/L	Separate dedicated xylose uptake system	Cellulase (-)	[158,159]
T. pentosaceus strain DTU01	70° C	Liquid pretreated Rapeseed straw (20% *v*/*v*)	2.96 g/L	Can use both	Cannot tolerate high inhibitor concentration	[160]
T sp. strain NTOU1	70 °C	Rice straw hydrolysate (15% *w/v* xylose equivalent)	3.9 g/L	Can utilize xylan	Cannot utilize cellulose	[161]
G. thermoglucosidasius	60 °C	Corn stover (5% *w*/*v*) Prairie cord grass (5% *w*/*v*)	3.72 g/L 3.53 g/L	Has high ethanol tolerance (10% *v*/*v*)	Cannot utilize glucose and xylose simultaneously	[151]
G. thermoglucosidasius strain TM242 (Δ*ldh*,Δ*pfl*, and *pdh*^{up})	60 °C	Palm kernel cake (8.36 g/L palm kernel cake hydrolysate)	9.9 g/L	Reduced formate, lactate and other by products	Cannot utilize glucose and xylose simultaneously	[144]
K. marxianus YRL 009 (*amy*$^{+}$ and *amg*$^{+}$)	42 °C	Cassava starch (20% *w*/*v*)	79.75 g/L	Increased ethanol production	Expresses amylase and glucoamyalse	[162]
M. thermoacetica (Δ*pdul1*$^{-}$), (Δ*pdul2*$^{-}$ and *aldh*$^{+}$)	55 °C	Forest residue hydrolysate (4.5% *w/v* glucose equivalent)	0.63 g/L	NA	NA	[163]

4.2. Increasing Ethanol Production

4.2.1. Physio-Biochemical Factor Optimization

To make downstream separation economical, it is desired to have 10–14% (*v*/*v*) of ethanol in the fermentation broth [164]. To increase the bioethanol production from the baseline yield, several physical, chemical, and biochemical factors viz. increased substrate concentration, improved availability of fermentable sugars, optimization of fermentation physicochemical parameters, reduction in inhibition components of pretreatment, fermentation, etc. had been studied and optimized using one factor at a time (OFAT) or statistical approaches. An increase in the food waste (glucose equivalent) from 43 to 172 g/L resulted in increased ethanol production from 12. to 45.4 g/L [147]. Statistical optimization is better than OFAT as both the main factor effects and interaction effects are taken into account in the former. The statistical optimization of NH_2SO_4, KH_2PO_4, yeast extract, and inoculum amounts using response surface methodology (RSM) increased the ethanol production using the food waste hydrolysate from 34 to 77.6 g/L [165]. In another statistical optimization study for enzymatic saccharification (pH, temperature, and enzyme concentration) and bioethanol production process (pH, temperature, and fermentation time), using food waste, reducing sugars, and an ethanol yield, respectively, of 117 g/L and 57.6 g/L were obtained [166]. Sometimes, even after optimization, the process yields do not increase once a plateau phase is reached. The modifications in the batch processes such as fed-batch, continuous, or semi-continuous can rescue the thwarted production yields in the batch processes. Yan and coworkers (2012) carried the fed-batch enzymatic saccharification of food waste increasing the ethanol production from 63 g/L in batch saccharification to 90.7 g/L in the fed-batch mode [20]. Similarly, in a consolidated continuous solid-state fermentation of food waste, the amount of ethanol produced was 58 g after 5 cycles of 40 g bread crust addition in 30 h; 38 g after 3 cycles of 160 g of potato chips; and 60 g with 8 cycles of 16 g rice grain. Furthermore, carrying ethanol fermentation in a continuous mode can cut down the enzyme costs, making the process more economic, and it can simultaneously remove the ethanol produced. Thus, optimization of the process parameters and process advancements can aid in increasing the ethanol yield.

4.2.2. Cell Addition

One of the critical requirements in the bioethanol bioprocess is to obtain and maintain a high microbial count optimal for bioethanol production during fermentation, as the higher cell density can accelerate fermentation rates, eliminate/reduce the lag phase, and promote inhibitor tolerance [167]. An increase in the microbial count and ethanol has also been successfully achieved by use of low-intensity ultrasonic waves by enhancing the expression of key enzymes in the metabolic pathways, increasing cell membrane permeability. Ronghai and coworkers showed that the use of ultrasonication treatment at 28 hz when applied to 7.5 L bioreactor increased the cry cell weight by 17.3% and ethanol by 30.8% as result of the increased intracellular Ca^{+2} concentration, increased enzyme activities viz. hexokinase (+59.2%), phosphofructokinase (+109.5%) and pyruvate kinase (87.27%) [168]. The analysis of yeast cells under scanning electron microscopy showed that the cells had wrinkles leading to increased cell membrane permeability. Several studies have shown that the addition of active microbial cultures at regular time intervals helps to increase the ethanol production. Carrillo-Barragan and coworkers showed that adding the microbial cultures after 3 days produced significantly similar ethanol concentration (56.85 mM) when compared to 14 days of microbial culture transfers (62.05 mM). Mixed cultures obtained from sheep rumen and anaerobic sludge helped to increase the ethanol production using the organic fraction of municipal waste [169]. Bibra et al. also added actively grown microbial cultures that helped to reduce the time of maximum ethanol production from 10 to 5 days [106]. The microbial cultures in the exponential phase are able to propagate faster and carry out the metabolic activity to produce more ethanol. Hence, the addition or recycling of cells ensures continuous ethanol production.

4.2.3. Inhibition Relaxation

A pretreatment step to obtain sugars becomes essential with the wild-type *Saccharomyces* spp. [142]. The complexity of FLW results in the various sugars available in the sugar hydrolysate obtained after pretreatment. *Saccharomyces* grows at a faster rate, and using simultaneous saccharification and fermentation might not work well, as the substrate limitation might impact the cell count and cell metabolism. A possible solution to this challenge might be the delayed inoculation of *Saccharomyces* so that there is enough sugar for the organism to thrive and increase the cell count. Paulova and coworkers delayed the inoculation by 12 h that helped to eliminate the carbon limitation in the early stages of the SSF [170]. The gradual feeding of the pre-hydrolyzed medium helped to increase the ethanol from damaged rice with 0.37 g/g sugar. An organism with the ability to cometabolize different sugars will be advantageous compared the microorganisms who cannot. Glucose is easily metabolized compared to other sugars such xylose, galactose, fructose, etc. [106]. Improving the inherent capability of the organism to cometabolize the sugars can aid in increasing the bioethanol yield. In addition to that, enhancing the ability of the organisms to withstand inhibitors will also aid in the increase in bioethanol. According to analysis data, 200.0 g/L food waste hydrolysate usually comprised 7.0–10.0 g/L lactic acid and 3.0–4.0 g/L acetic acid. It had been reported that lactic acid and acetic acid present together in a medium exhibited a highly synergistic inhibitory effect to yeast [18].

4.2.4. High Solid Loading

High-gravity ethanol fermentation with solid loading levels of 25–30% *w/v* solids can aid to achieve the desired 10–14% (*v/v*) ethanol concentration [171]. Rygielska and coworkers investigated the simultaneous saccharification and fermentation (SSF) of waste wheat–rye bread at high solid loading (300 g/kg) [172]. The enzymatic liquefaction conditions were modified based on the thermal properties of starch gelatinization and compared to the temperature optimal for α-amylase activity (85 °C). Modification of the enzymatic liquefaction conditions resulted in further improvement of the ethanol yield. The best results were obtained when waste bread was liquefied at the final temperature of gelatinization (59 °C), resulting in final ethanol concentration of 128.01 g/L yielding 425.04 g/kg of dry matter and 95.93% practical yield, whereas 416.09 g/kg and 93.91% were obtained for liquefaction at 85 °C. In another study, the by-products of dates having high concentrations of sugar have been used for ethanol production. Using *Bacillus amyloliquefaciens*, the ethanol concentrations from the syrup of dates (175 g/L and 360 g/L of total sugar) were 90 and 92 g/L, respectively [173].

4.2.5. Bioreactor

The use of a bioreactor in the bioprocess development provides a controlled environment that can support the cell growth, substrate conversion and productivity of the biological process better while reducing the overall cost of production of desired products and making the process economical. The reactor configuration, the operative conditions, and the mode of operation mode have a critical impact on the yield and productivity of the bioprocess. The majority of the bioethanol production bioprocesses developed with FLW are submerged fermentations. The common configuration for the bioreactors used in the submerged fermentation is rushton impellers, baffles, aerated vessels, and continuous stirring for batch processes [106,135,159,168,174]. The economic bioethanol production using FLW will require high solid loading. High solid loading can sometime experience mixing challenges creating under aerated pockets where the dissolved oxygen is not similar to the rest of the bioreactor. Loizidou and coworkers developed a dual horizontal bioreactor system for bioethanol production using FLW that harbored a variation of double helical ribbon impeller to mix the contents in place of commonly used Rushton impellers to overcome the resistance experience during the mixing of the high solid content in the bioreactors [175]. The first horizontal stainless steel jacketed reactor had a capacity of 100 L and carried the pretreatment and prehydrolysis of the FLW, whereas the second stainless steel reactor with a capacity of 200 L was used for fermentation. The ethanol amount produced in the fed-batch process using the dual horizontal reactor system was 53.9 g/L with a yield of 14.87 g/g dry FLW. A biofilm bioreactor system was used for bioethanol production using rice straw hydrolysate to carry out multistage continuous operations as a packed bed reactor [176]. Two biofilm reactors were designed with different volumes with the first reactor having twice the volume of the second reactor and hence a different dilution value. The reactor consisted of a cylindrical bulb filled with GP110 plastic composited corn silk as a biofilm support that was 5% of the 1 L working volume (vessel 1 or V1) and 500 mL working volume (vessel 2 or V2). The use of two fermenters with one fermenter volume twice the volume of a second fermenter aids in maximizing the bacterial cell growth early in the multistage system. A biofilm of *Zymomonas mobilis* strain ZM4 was grown on plastic composited corn silk at a temperature of 30 °C and pH 5.8 with medium replacement every day for 5 days. The fermentation of rice straw hydrolysate produced was completed in 3 days, media was collected for the product separation, and the tank was filed again with rice straw hydrolysate for the next cycle of fermentation. Three consecutive batches gave a yield of 0.36–0.38 g/g ethanol. The continuous fermentation in a series of reactors with a progressive increase in dilution rates enhanced the ethanol concentration and product yield.

4.2.6. Other

Shortening the fermentation time is also an important aspect that can help to (1) increase productivity, (2) reduce process operation cost significantly, and (3) lower contamination probability, as contamination probability increases with the fermentation elongation (4). Producing a biofilm of co-culture of *Aspergillus niger* and *Saccharomyces cerevisiae* on the plastic composite support helped to reduce the maximum enzyme (glucoamylase) activity time from 96 to 24 h and reduced the total fermentation time from 120 to 72 h using potato peel waste without any impact on the ethanol production [148]. The use of immobilized cells and enzymes can help to reduce the production cost by optimizing the cell and enzyme recovery and activity [177,178]. The progress in nanotechnology has offered new approaches where the attachment can be completed on nanoparticles, nanofibers and nanorods. NiO nanoparticles helped to improve the different stages of bioethanol production from potato peels and gave a bioethanol yield of 32 g/L by *Saccharomyces cerevisiae* BY4743 compared to 22.5 g/L when no NiO nanoparticle was used [179]. In another study, the treatment of thermophile *Geobacillus* sp. WSUCF1 by cold plasma for 4 min increase the glucose utilization rate by 74% (w/v) and biomass yield by 60% due to the increase in membrane fluidity [180].

Thus, different approaches can used to optimize and increase the bioethanol production using FLW. The choice of approach will depend upon the criticality of the variable on the process performance. Establishing a correlation of process performance with process parameters will strengthen the decision-making process for process optimization and production increase.

5. In Situ Ethanol Separation and Recovery

The ethanol separation from the broth in food waste has not received the same attention as the bioprocess optimization aspect. Figure 6 shows the overview of bioethanol production using FLW. For ethanol production to be economical, the ethanol concentration in the fermentative broth should be ≥4% (v/v). However, as the concentration increases to 120 g/L, the ethanol becomes toxic to the fermenting microorganisms [181]. *Saccharomyces cerevisiae and Zymomonas mobilis* experience 50% inhibition at 40 g/L and 50 g/L ethanol, respectively, in the broth [182]. Hence, several methods had been researched and developed to remove the ethanol from the fermentation broth in situ and maintain a continuous fermentation for higher ethanol production. Only methods involving the in situ separation of the ethanol from the fermentation broth that can have a positive impact on the bioethanol production and processes that can aid in the final product separation are discussed in this review. Vacuum extraction, gas stripping, adsorption, solvent extraction, pervaporation, vapor permeation, and membrane distillation had been the most commonly used methods for removal of the ethanol from the fermentation broth [125,183,184]. Distillation is the most commonly employed separation process for the ethanol extraction from the fermentation broth, but it has high heat demand and low thermodynamic efficiency [185]. An input stream with 8–9% (w/w) ethanol is considered good by industrial standards for an economical distillation process [186]. The fermentation broth consists of several volatile fatty acids, organic acids and cell debris produced during fermentation. Due to the presence of such compounds in the fermentation broth, the in situ bioethanol separation from the vapor is more favorable compared to the fermentation broth. The metabolic pathways of ethanol production produce different by-products depending upon the host of fermentation. Yeasts produce glycerol and propionic and malic acid, whereas bacteria produce acids such as acetic acid formic acid, butyric acid, propionic acids, alcohols, methanol, propanol, butanol, etc. Gas stripping with insert gases and vacuum removal are very commonly employed methods for the in situ removal of the ethanol from the fermentation broth. An inert gas is added to the fermentation broth from the aeration line to remove the ethanol as vapors, which is stripped from the condensation column or a distillation column hooked to the bioreactor. Using N_2 gas for stripping increased the ethanol amount in the stripper condensate by 3.4, achieving > 90% of the ethanol recovery from the fermentation broth [184]. Increasing the temperature closer to the ethanol water azeotrope point aids in better ethanol removal from the broth during gas stripping. Increasing the bioreactor temperature to 80 °C from 65 °C at 8 psi for 30 min during nitrogen purging every 24 h aided in better ethanol removal from the fermentation broth during FLW waste fermentation [159]. The gas stripping helped to remove and concentrate the ethanol from 11.2 g/L in the fermentation broth to 29.8 g/L in the stripped liquid. The flash vaporization can remove the ethanol from fermentation broth at a higher temperature without any insert gas addition. A simulation work to separate and concentrate ethanol produced from food waste fermentation showed that the ethanol in the fermentation broth can be concentrated to a mass percentage to 2.87% from 0.8% (*w*/*w*) by flash vaporization at 99 °C [186]. The use of membrane separation for ethanol separation from the fermentation broth has been constantly met with fouling challenges that result in the reduction in the separation factor and flux. To recover the separation, the membrane requires washing at regular intervals to remove the organic acid and protein causing the membrane fouling. Targeting ethanol separation from vapors than broth can help to address the membrane fouling challenge. Sun and coworkers employed a modified vapor permeation method using polydimethylsiloxane (PDMS) membrane for ethanol extraction from the fermentation broth [183]. No reduction in the separation factor was observed until the end of the fermentation. The ethanol productivity rate increased to 3.3 g/L/h from 2.13 g/L/h with vapor permeation, as the in situ ethanol removal reduced the inhibition on the fermenting microorganism. Using vacuum is another method used to remove the ethanol from the fermentation broth. In another study, the ethanol concentration was increased by 9% from 114.5 to 125.3 g/L by using a vacuum set up to remove ethanol from the fermentation broth in situ [125]. The vacuum application obliterated the need for increasing temperature, using an inert gas, or challenges observed with the membrane fouling. A constant search for new techniques to extract ethanol is still ongoing with a recent approach including the use of molecular-sieving carbon (MSC) after stripping the fermentation broth with CO_2 [187]. The simultaneous separation of the ethanol resulted in 37 5 (*w*/*v*), 35% (*w*/*v*), and 40% (*w*/*v*) of ethanol, respectively, from bread crust, potato chips, and rice grain [188]. As the advancement in the concentration and separation methods is made, a conclusive method can be developed with ease of application from the lab scale to the pilot scale.

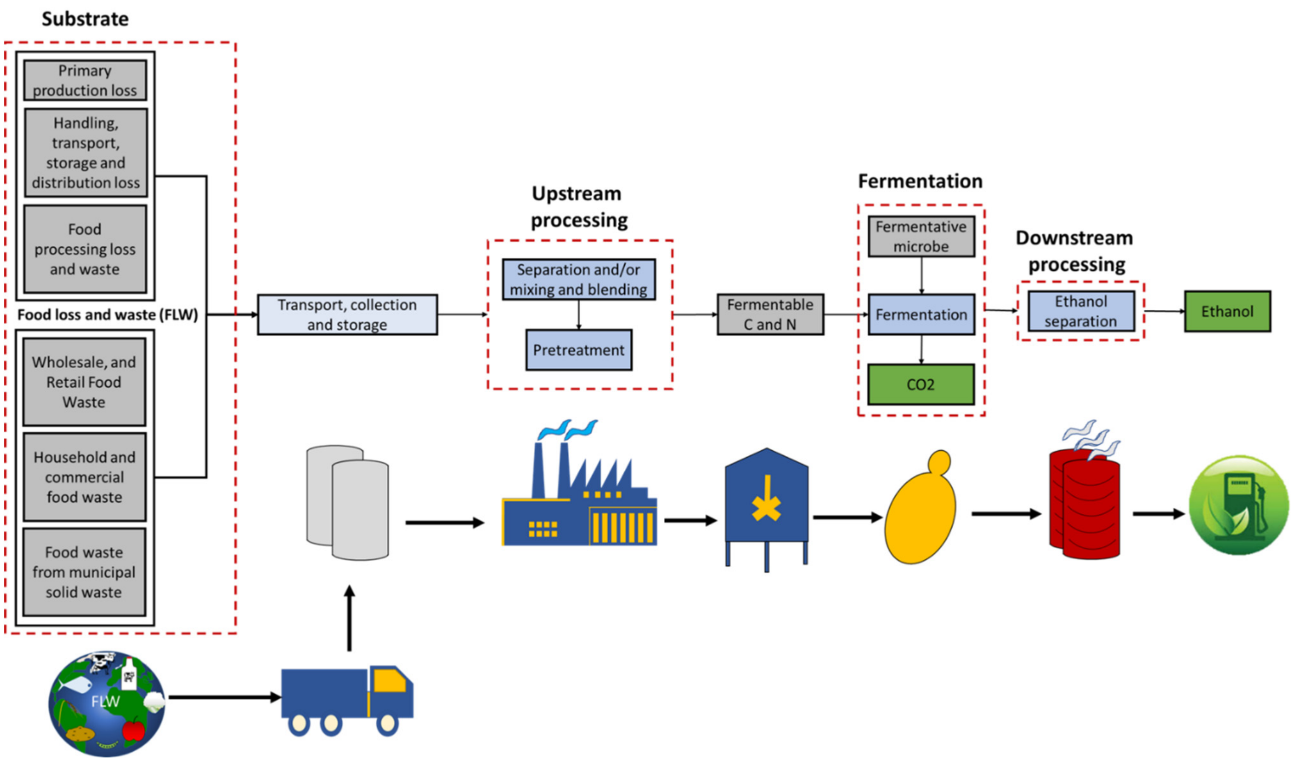

Figure 6. An overview of the bioethanol production process using FLW. The bioprocess operations start with the potential source separation, transport, collection and storage of the FLW at the production site. The FLW obtained is subjected to upstream processing to obtain the carbon and nitrogen required for the fermentation. The fermentation by an ethanologenic microbe produces ethanol in the broth which after downstream processing is separated from the broth to obtain bioethanol.

Ethanol separation from the fermentation broth is not the only challenge faced for downstream processing. The presence of competing products and organic acids from the FLW and the fermentation broth can create challenges in economic separation of the ethanol. In addition to that, the type of FLW used consisting of pectin can also pose challenges for the downstream processing, as pectin can be converted to methanol during fermentation that can cause the separation challenges [189–191]. In the batch processes, the carbon source is usually utilized to exhaustion; however, in the fed-batch processes, the remaining amount of carbon source can interfere in the product separation. Silicalite, a zeolite-like structure mainly consisting of five-membered rings of silicon–oxygen tetrahedra, was shown to adsorb ethanol independent of ethanol broth concentration (2–8% *w*/*v*) and temperature (30–60 °C) without any adsorption of glucose [182]. Such adsorption can ensure the carbon source is returned back to the bioreactors for further fermentation and prevent any inhibitor production during downstream distillation.

6. By-Products

FLW is rich in carbohydrates and nitrogen. The by-products in the fermentation process depend on the substrate being used and the microorganism being used. Lignocellulosic biomass has less nitrogen compared to FLW consisting of agricultural products fit for human and household use. Post-fermentation, an organic fertilizer grade material can be obtained from the solids. The solids (25% *w*/*w*) obtained from the bioethanol plant using sugarcane bagasse for ethanol production had 300 mg/L phosphorous and <1 mg/L nitrogen. When the fertilizer obtained from fermentation solids was applied to the snap bean as a phosphorus-rich fertilizer, the yield was 298 g/plot vs. 94 g/plot for phosphorous fertilizer and 51 g/plot for the control with no fertilizer [192]. The fermented broth also contains several organic acids viz. acetic acid, propanoic acid, butyric acid, etc. which can be used for methane production. An integrated process with bioethanol, biomethane and fertilizer will help to realize the zero-waste concept. As per an estimate for 1 kg of organic fraction of municipal food waste (OFMSW), a composition of starch (586.3 g), cellulose (56.3 g), lipid (64.5 g), and protein (83 g) can be theoretically converted to 364 g of ethanol or 383.2 L of methane in an ideal process [35]. The solids from the pretreatment can also be mixed with the solids from fermentation for methane production. The mixing of the bread waste post-fermentation solids with solids from acidic pretreatment and enzymatic pretreatment gave a biochemical methane potential of 345 and 379 mLCH4/g VS, respectively, after 114.9 g/L of ethanol production [135]. The organic acids can also be removed from the broth, but the process's economics needs and return on investment need to be taken into consideration for such processes. One particular by-product that is not given much attention is CO_2. CO_2 is produced proportionally in a ratio of 1:1 to ethanol and thus is by far the greatest carbon and energy sink in the bioethanol production process. A common strategy that is employed in the commercial plants is to convert this CO_2 into dry ice [193,194]. POET, a key player in the ethanol industry, also produces liquid CO_2 that can be used for beverage carbonation, food processing, municipal water treatment, fire suppression, agricultural applications, surface cleaning etc. [194–196]. The improvement in bioprocess where the CO_2 can be reduced or reutilized in the bioethanol process will help conserve and/or convert more of the lost energy in FLW.

7. Future Directions

The increasing pace of energy resource depletion and FLW generation is a real concern. The bioethanol production from FLW can address both the issues; however, the technology for deployment is not mature enough yet. Addressing the challenge of variability and availability will help to ensure continuous production. The pretreatment will be a necessity, but a consolidated bioprocess with an organism capable of producing hydrolytic enzymes can improve the process economics. A collaborative effort and open communication between the industry and academia can effectively shorten the time period for technology maturity. A strategic planning for landlocked but highly populated regions in the world can make it an economical success and role model for other places. Such processes will not only be able to address the challenges of increasing population and decreasing resources but will provide stability to energy prices and economic development to countries with minimal resources.

8. Conclusions

The unplanned anthropogenic activities have warranted the need for developing sustainable solutions to aid and sustain the growth and proliferation of current and coming generations. The demand for alternative biofuels is at unprecedented levels due to increasing fuel prices, growing population, and limited resources. The technology readiness level and economic success of bioethanol make it a biofuel of choice. In spite of all the advantages bioethanol offers, a food vs. fuel debate will likely challenge the status quo of bioethanol usage in the coming years if the current use of food materials for bioethanol production is not replaced by alternative sustainable substrates. It is quintessential to find new sustainable resources to produce the bioethanol, as the world will grapple with increased energy demands in the coming years. An enormous amount of FLW is generated globally despite the concerns of increasing food scarcity for the growing population. A global effort is being put forward to address the issues of food and energy scarcity and wastage by all the nations. FLW can be an excellent source for bioethanol products, as it is rich in nutrients and minerals and aid in achieving these goals. The abundance of carbon and nitrogen source favor the use of FLW as a substrate for bioethanol production. The biggest challenge in bringing the FLW-based bioethanol production to reality is to ensure the availability of FLW year round with limited variation and addressing the variability in the FLW. The FLW variability, due to different components depending upon at which stage of the food value chain they are generated, presents challenges but can also be used to fine-tune the processes to obtain required substrates, enzymes, cultivate organisms, and products. A successful bioprocess development will require the development of an economic pretreatment process that can ensure high sugar content with minimal inhibitor production. The use of a microorganism capable of consolidating different steps of the bioprocess in a single reactor will greatly reduce the cost and make the process economical. *Saccharomyces cerevisiae*, *Zymomonas mobilis* are some of the commonly used microorganisms used for developing FLW-based bioethanol bioprocess. The wild-type fermentative microorganisms might not be able to consolidate all steps, but the previous research and increased metabolic understanding of these microorganisms outweigh the disadvantages viz. lack of enzymatic machinery, inhibitor tolerance, substrate preference, etc. encountered. The use of recombinant, co-cultures and/or thermophilic microorganisms can help to improve the process readiness level for commercialization. Ensuring high-ethanol titers will be a key to make the overall process economical. The by-products can offer some cash incentive to offset the costs, but the overall process economics and the rate of return on investment will be crucial to determine their role to make the process profitable.

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