Review Paper

Lignocellulosic biomass and industrial bioprocesses for the production of second generation bio-ethanol, does it have a future in Algeria?

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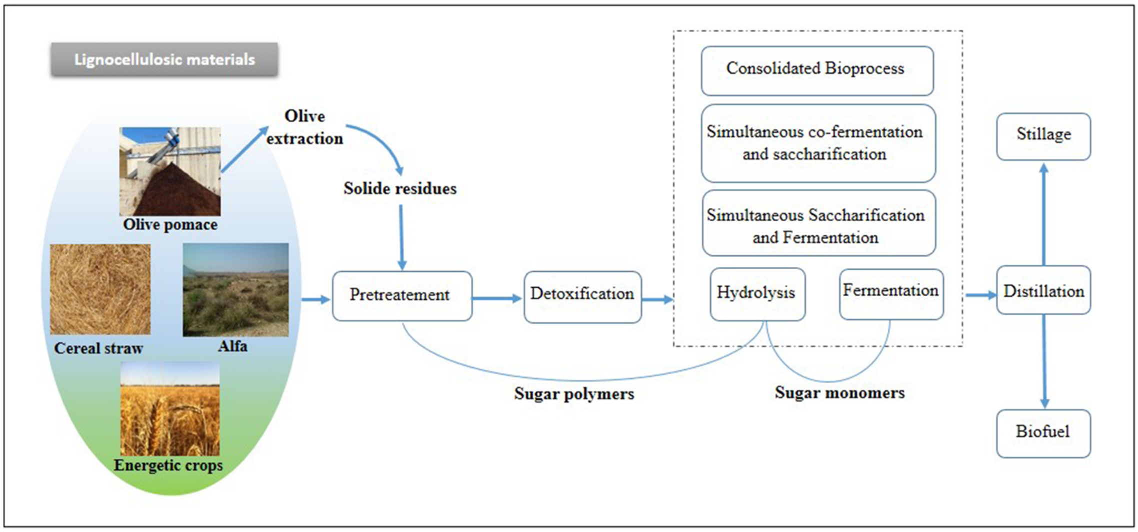
Abstract
Algeria is facing two serious constraints, energy shortage and environment pollution. To overcome these two problems, renewable energies are the best sustainable alternatives. In this context, Algeria Government has established in 2011 a program for the development of renewable energies. The prospective results show a substantial contribution to supplying national energy demand as well as some significant environmental benefits, namely through major greenhouse gas savings. In fact, lignocellulosic sources as Algerian Alfa, olive pomace and cereal straw could provide up to 0.67 Mtoe which represents 4.37% of the energy consumption of transport sector in Algeria. In the same vein, introducing energy crops and dedicated cereal crop technologies allows Algeria to progressively increase its renewable energy supply. Up to 73.5 Mtoe and 57.9 Mtoe can be produced from the two cited resources respectively. That is more than the national energy consumption which reached 60.96 MToe in 2018.

Graphic abstract



Keywords Lignocellulosic biomass · Bioconversion · Bioethanol production · Energy crops · Algerian Alfa · Olive pomace

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1 Introduction

The depletion of fossil resources and the environmental pollution (global warming, acid rain, smog, etc.) caused by greenhouse gas (GHG) emissions, such as carbon dioxide CO_2 from the exploitation of oil [1, 2], justify the search for alternative technologies capable of protecting the environment and reducing the dependence to these fossil fuels [3]. Currently 8–14% of global energy consumption is based on biomass which includes all the organic matters such as plants and forests residues, food and agricultural waste, as well as both solid and liquid domestic wastes [4]. Indeed, the biomass is recognized as a renewable resource that can reduce GHG emissions—of CO_2 sequestered in biomass (the CO_2 which was taken from the atmosphere during the growing stage of the biomass) [5, 6].

Furthermore, in order to reduce CO_2 emissions, many jurisdictions have planned to deplete the emission levels by 2030 (40% levels for European Union; 26–41% for Canada; 38–48% for Japan; 25–30% for United States; 19–34% for China and 13–17% for India,) compared to 1990 emission levels [7]. Other countries like Denmark have very ambitious targets since their energy policy suggests that 100% of the energy consumption would come from renewable sources by 2050 [7–9].

Lignocellulosic biomass that includes agricultural and farming organic wastes, agro-food industries residues and crop residues, is the most abundant renewable organic resource to be considered as raw material for bioconversion to bioethanol in the planet. However, it is important to notice that this may differ from one region to another. Some dry regions of eastern and southern Africa, the Horn of Africa, western South America etc., are the most affected regions by severe droughts which leads to a wide range of health and economical problems especially for agricultural communities.

There are various technologies to convert biomass into a reusable energy form. These technologies change energy directly to usable forms such as heat and/or electricity [10], or to other forms like biogas and bioethanol. The latter is increasingly replacing products based on fossil fuels. In fact, bioethanol is considered as an oxygenated fuel, it contains 35% of oxygen which allows a particular reduction of GHG emission and Nitrogen oxides NOx emissions caused by combustion of the fuel. The bioethanol–gasoline mix can significantly reduce petroleum use and GHG emission [11]. Both the U.S and Brazil remain at the top list of ethanol producing countries (85% of world production). While the U. S bioethanol industry is breaking records in production, consumption, and exports, generating more than 59 billion liters mostly from corn. Brazil produces the biofuel from sugar cane, consolidating its second position reaching 32.63 billion liters in 2019 [12]. However, it varies according to the sugar market evolution. In contrast, the European countries, which are high consumers of bioethanol for cars, contribute very little to the global production. The current bioethanol production is approximately 5.5 billion liters [13].

A 100% renewable economy would give a sustainable solution to the concerns raised by energy security, climate change and pollution [14]. Transport sector emissions can be decreased through a variety of changes in the transport system, alternative transport fuels like gaseous fuels, biofuels, and electricity, can reduce emissions significantly. Other advantages of these fuels include the diversification of energy sources and the reductions of lifecycle greenhouse gas emissions [15]. During the economic crisis of 2008–2009, many countries implemented fleet renewal schemes claiming their economic importance and also their pollution reduction benefits [16]. On the other hand, biofuels represent a considerable reduction in the transportation sector dependence on oil. Their promotion is easier to implement than that of alternative gaseous fuels since their use in mixture with petroleum fuels requires neither the development of new distribution infrastructures nor the adaptation of vehicles [17].

Algeria is currently facing a plethora of serious problems regarding fuels and environment. Revenues from fuel market are estimated to decrease by almost 50% ($ 34 billion in 2015 compared to $ 68 billion in 2014) [18], and on the other hand, there is a trend for depletion of fossil energy resources as well as for pollution and proliferation of all kinds of waste such as forest residues, agricultural, industrial and urban wastes. Most of these wastes are often removed by burning [19], although they represent an abundant resource for bioconversion into energy. As a consequence, according to the latest report of the World Health Organization [20], the air quality in Algeria is characterized by a high pollution rate exceeding that of highly industrialized countries such as Germany, France and even the United States. Indeed, the two major sources causing air pollution in Algeria are vehicles traffic and waste combustion. Algiers, like many other metropolitans, is facing a serious atmospheric pollution from the extremely high levels of particle pollution, ozone, benzene and lead. Their pollution is very high compared to WHO standards and consequently, the urban population is mostly exposed to its negative effects [21].

Algeria's energy needs are met almost exclusively by hydrocarbons. The economic growth since 2001 is based on the public demand driven mainly by hydrocarbon revenues. Nevertheless, oil and gas are two natural resources, non-renewable and they cannot be drawn endlessly. The unlimited growth of their demand is incompatible with their limited availability [22].

As reported by the Algerian Ministry of Energy, the national energy consumption reached 60.96 million tonne oil equivalent (Mtoe) in 2018 [23]. Studies conducted by CHERFI [22] about the future of energy in Algeria on the horizon 2020–2030 have presumed that the Algerian market would require 61.5 Mtoe of primary energy in 2020 and about 91 Mtoe in 2030; the increase of the energy demand would range between 2.8 and 4.3% per year (assuming an economic growth rate between 3 and 5% in parallel to a population growth of 1.6% per year for the period 2007–2030). According to the official figures and the predicted ones, we assume that these studies are quite logical. Therefore, all these considerations justify the need for a strong integration of renewable energies into the long-term energy supply strategy starting from today.

On the other hand, according to the national statistics office, the total agricultural area (TAA) is of about 42.4 million hectares. The TAA comprises 8.43 million hectares of useful agricultural area (UAA), 32.9 million hectares of pastures and rangelands that serve only for grazing animals, and one million hectare of unproductive farmland that includes farms, buildings, yards, threshing grounds, paths, canals, ravines, tracks…etc. In fact, The Algerian agriculture uses only 17% of the national territory i.e. 238 million hectares [24, 25]. Indeed, these grazing lands are a real neglected fortune that can be used for energy purposes.

This work focuses on the identification of lignocellulosic biomass sources in Algeria, and describes a real and referenced inventory of the bioenergy potential in this field based on bioethanol production. However, the estimation of the recoverable energy from this renewable biomass could be easily adapted for biogas containing methane or bio-hydrogen. The valorization potential of this biomass could also be further determined on a bio-refinery point-of-view leading to different bio-based compounds for a lot of innovative applications [19–21].

2 Lignocellulosic biomass

Lignocellulosic biomass is one of the most abundant renewable resources on earth. Mainly composed of cellulose, hemicelluloses and lignin. Unlike first generation biofuel which are usually produced from starch and sugars (sugar beet and sugarcane). Lignocellulosic biomass represents the potential fuel alternative resource to overcome the global energy crisis to produce second-generation biofuels and biosourced chemicals and materials without compromising global food security [27].

This biomass is derived from agricultural and forestry economic sectors such as residues or by-products of wood processing, dedicated crops from woody or herbaceous plants grown in energy crops fields. Among the agricultural residues, wheat straw is the main biomass feedstock in Europe and the second largest in the world after rice straw [28]. In this work, the energetic potential of Alfa "*Stipa tenacissima*" will be mainly discussed as well as olive pomace, wheat and cereal straw for their bioconversion to bio-ethanol. The potential will be based on the degraded cultivable land that can be used to culture bioenergy plants in Algeria and on the energy that could be recovered from the cited resources.

2.1 Energetic potential of Algerian Alfa fibers *Stipa tenacissima* for the second-generation bioethanol production (G2BP)

Alfa, also called halfah, or esparto grass, is typically a fast growing Mediterranean perennial plant [29]. This herb thrives spontaneously and especially in arid and semi-arid environments. Alfa is a common grass in North Africa, particularly in the highlands of Algeria. One hectare can produce more than one tonne of dry biomass per year, but the yield is far from such an adventurous rate [30]. This herb covers approximately a surface of 4 million ha [31]. It's biological cycle comprises two growing seasons (fall and spring) and two latent seasons (winter and summer) [32]. Indeed, it is used in artisanal field, in agriculture and in paper industry [29, 33].

The interest for this crop as a potential source for G2BP lies in its adaptation to a semi-arid climate; Esparto grass grows in almost all the geomorphological units. However, the most dense populations are found in low-lying areas and on permeable glacis. The Alfa plant seems to prefer calcareous soils that are shallow and permeable with a very sandy texture. It does not adapt well to soils with gypsum, salt, clay, or loam content. Moreover, Alfa thrives in a wide range of bioclimates and it is resistant to large variations in temperature. However, it's optimum growth is achieved in arid superior and semi-arid lower bioclimatic stages [32].

In fact, many authors suggested that the cultivation of drought-tolerant energy crops should be the most relevant choice in terms of both adaptation and environmental sustainability [34]. Recently, studies have been carried out to optimize the pretreatment of Alfa fibers for the G2BP [26, 27].

Alfa is composed of cellulose, hemicellulose, lignin and ash. Its biochemical composition may slightly differ depending on climatic and soil conditions i.e. in the ranges (w/w dry weight) 63–48%, 22–9% and 12–18%, respectively [26–28]. Its high concentration in polysaccharides gives Alfa a real potential for its integration as a raw material for bioethanol production [35].

The potential ethanol yield from Alfa was studied recently and for the first time by Zaafouri et al. [36]. The yield of 1 L biofuel from 10 kg Alfa dry fiber was achieved after sulfuric acid H_2SO_4 pretreatment at 3% (41.27% of reducing sugars). Another study conducted by Semhaoui et al. [35], aimed to optimize the thermomechanical pretreatment conditions for G2BP from Alfa; saturated steam pressure followed by a flash decompression to vacuum pressure and a concentration of 5% of H_2SO_4 was efficient to obtain a maximum reducing sugars yield of (95%), unfortunately this study stopped at this step. However, this Alfa-bioethanol process could be improved. Economic and technical feasibility studies are needed to assess the product's suitability and the process' reliability for sustainable commercial application.

The annual production of Alfa can reach up to 250,000 tonnes per year [33, 29]. The exploitation has reached only 3 million ha from the total of Alfa lands, whereas more than one million ha of Alfa territories have not been exploited and used effectively. As a result, more than 62,500 tonnes of unexploited Alfa could be recovered for bioethanol production. Theoretically, and based on the first reference, almost 6.25 million liters of ethanol could be produced from these areas with an energetic potential of 3150.13 Toe.

Algerian highlands, which occupy about 9% of the total area (21,435,660 ha), are characterized by a semi-arid climate (rainfall between 100 and 400 mm/year). Almost two thirds of the lands are cultivated [25]. Therefore, more than 7 million ha could be exploited for Alfa cultivation, since the bioclimatic conditions are suitable for its growth. Theoretically, more than 7 million tonnes of dry biomass could be generated from these areas. Thus, more than 700 million litres of ethanol with an energetic potential of 0.3 million Toe could be produced.

Besides to its energy importance, the environmental benefits from Alfa cultivation are phenomenal; the desertification process is so important in these areas due to drought, weakening of soils subject to wind erosion. Alfa cultivation forms a key component for arid and semi-arid ecosystem sustainability. Its resistance to long drought periods, the protection of soil against erosion, its resprouting ability, and its ecological amplitude make it a very valuable species with a view to using it in restoration programs.

2.2 Energetic potential of olive pomace for G2BP

Olive pomace is a by-product of olive oil extraction process. Depending on the technology used, about 2–3 tonnes of olive pomace (solid waste) and from 2000 to 6000 L of vegetable water (called Amurca) are released per tonne of olive oil extracted [39]. Both solid and liquid wastes from olive oil production cause serious environmental concerns. Their dangerous effects are derived mostly from their content in polyphenols which are very difficult to biodegrade. The vegetable water is much more harmful than urban wastewater, nevertheless it is frequently discharged into rivers or sewers [40]. On the other hand, oil pomace consists of a lignin-rich fraction (21.3% of total solids) and high contents of cellulose (55.4% of total solids) [41]. This gives a real potential for the integration of these wastes as a raw material for G2BP. Several studies have already been carried out to optimize their pretreatment thereto. They involve sugar extraction from olive pomace followed by enzymatic hydrolysis to extract simple fermentable sugars.

More precisely, the solid residues are first crushed into powder and dried before the extraction step with acid or base compounds. The powder is treated with dilute acid [42] or dissolved in a concentrated solution of hot sulfuric acid (100 °C) [43] or pretreated in an autoclave at different temperatures ranging from 150 to 250 °C) [44]. The basic pretreatment is carried usually with lime or hydroxide, sometimes intensified by ultrasounds, and followed by calcium carbonate addition to decrease the concentration of polyphenols that inhibit fermentation by yeasts [45]. After the pretreatment step, the extracted complex carbohydrates are treated with hydrolyzing enzymes (cellulase, glucosidase, etc.). The last step deals with the bioconversion of the released soluble sugars to produce ethanol in fermentor units in presence of microorganisms, such as *Kluyveromyces marxianus* a thermo-tolerant yeast [42, 44] or *Saccharomyces cerevisiae* [45]. In the same context, the yeast *Issatchenkia orientalis* was also used by Abu Tayeh et al. [43], and showed the best efficiency in the production of ethanol when supplemented with glucose, with an average yield of 3 g/100 g dried pomace.

In Algeria, the agricultural area dedicated to the olive sector is about 450,000 hectares covered by 56.3 million trees whereby 32.3 million are productive olive trees for food [46, 47]. Olive oil production has reached 80,000 tonnes in 2017 [48, 49]. And according to the ministry, the production should reach 120,000 tonnes in 2020 [50].

Therefore considering the amount of olive oil produced in 2017 in Algeria, we can estimate the annual quantity of solid residues at 165,600 tonnes that could be valorized in about 5000 tonnes of ethanol, with an estimated energy potential of 3500 toe.

2.3 Energetic potential of wheat straw and other cereals for G2BP

Wheat is the most widely grown cereal crop; it occupies 17% of all cropland on the planet. Wheat is a staple food for 35% of the world's population, and its production reached 733.8 million tonnes per year (2015–2016)

[51]. The volume of global wheat production needs to be increased to meet the growing consumer demand [52].

During the last decade, the national production of cereal grain has been higher than the 10 years average (2000/08) of 2.97 million tonnes Mt. The 2020 grain production is estimated at an above-average level of 4.9 Mt (about 20% below the record 2019 level), i.e.; 3.6 Mt of wheat *Triticum aestivum*, 1.2 Mt of barley *Hordeum. vulgare* and 0.7 Mt of oats *Avena. Sativa* [53] (Fig. 1). However, Algeria imports more and more cereals to fulfill its population's needs, needs that rise on average 231 kg per inhabitant per year (8 Mt needed for domestic consumption) [54, 55]. To face this decline in cereal production, the government aims to gradually increase its production and to support more the development of agriculture. Therefore, cereal straw may hold a great raw material for the ethanol production in Algeria.

Conducted chemical component analysis shows that wheat, barley and triticale straw contain a high amount of cellulose and has, at the same time, a low lignin and ash content [56]. Respectively the cellulose, the hemicellulose and the lignin content of wheat straw is between 33–40, 20–25, and 15–20 (% w/w) [57]. This makes straw an attractive raw material for its ethanol bioconversion [58].

The average straw yield can be calculated using the formula bellow, where the average wheat Harvest Index is around 0.45 [59]

$$\text{Straw yield} = \left(\frac{1 - \text{HI}}{\text{HI}}\right) \times \text{Grain yield}$$

Taking into consideration the 2020 grain production, the total straw production is estimated to be 4.395 Mt. The processes involved in bioethanol production from straw remain the same and include an appropriate pre-treatment to make cellulose and hemicellulose accessible, hydrolysis, fermentation and finally distillation as discussed below [49, 50]. In total, one tonne of biomass, based on dry matter, would currently produce between 200 and 230 L of ethanol. Optimization of both cellulose and hemicellulose conversion as well as fermentation processes could increase this yield to nearly 400 L [61]. Theoretically, about 879–1758□ million liters of ethanol could be produced from straw per year, with an energetic potential of 443,016–886,032□ Toes.

On the other hand, corn straw which consists mostly of leaves, stems and ears left on the field after corn harvesting [62]. This waste represents about half of the corn-crop yield (corn grain represents about 45% of the total dry matter yield of the cornfield) [53, 54], and it ranges from 3 to 4.5 tonnes dry straw per acre [64]. Corn straw consists of 36.8–37.4% cellulose, 22.2% xylan, 2.9–5.5% arabinan, 1.6% mannan, 2% galactan, 23.1% lignin and 5.2% ash (WT% dry) [56, 57]. The free access to corn cane and the high concentration of polysaccharides make it an ideal candidate for ethanol production [66]. In fact, corn production in Algeria has reached 25,720 tonnes in 2014 [67]. Assuming that corn grain yield is equal of straw yield, the amount of corn cane that can be sustainably harvested nationally is 25,720 tonnes [68]. On the other hand, the theoretical ethanol yield is about 250–350 L/tonnes of dry matter [69]. As a result, 6.43 up to 9 million liters of ethanol could be produced from this waste, with an energetic potential ranging from 3240 to 4536 Toe

The availability of cereal straw for bioenergy production is limited by the need to reserve an important part for traditional livestock markets, and the constraints of organic matter returning to the soil. However, a significant part

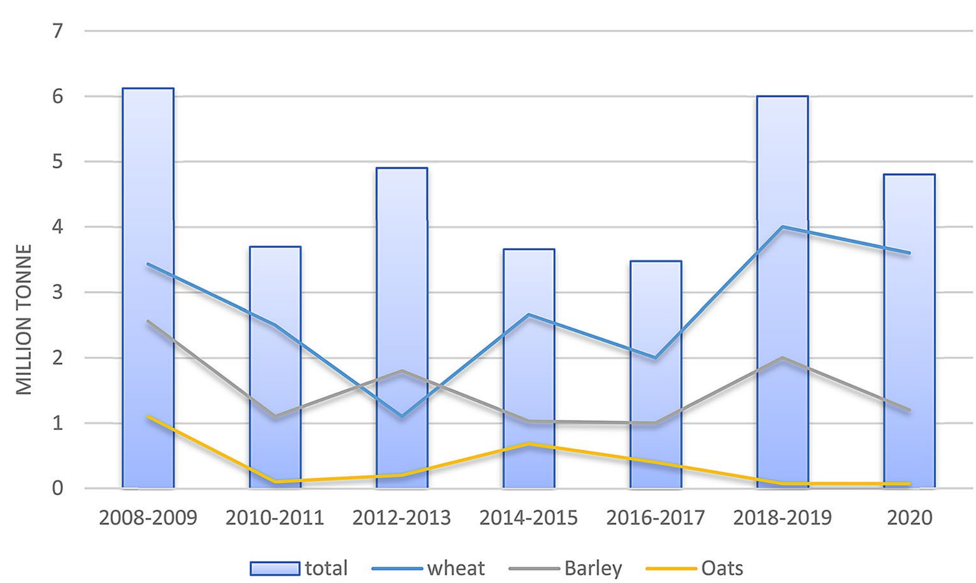

Fig. 1 Cereal productions in Algeria between 2008 and 2020

of these wastes can be valued at least to meet the local energy needs of the producing farms.

As a matter of fact; when we take into account the potentialities of agricultural lands in Algeria, the surface water and the mobilizable aquifers, Algeria can become an important agricultural country providing that we operate an effective strategy to exploit abandoned farmland and subsequently aim for self-sufficiency in cereals, which will allow the field of renewable energy with a very important amount of raw material, such as cereal straw and other agricultural wastes. Indeed, one hectare of cereals produces 3500 L of bio-ethanol and 3.5 tonnes of grains [70]. Theoretically 115 billion liters of ethanol could be produced from dedicated crops, with an energetic potential of 57.9 Mtoe. Table 1 summarizes the studied lignocellulosic biomass resources and their potential for biofuel production.

2.4 Energy crops as alternative sources of energy in Algeria

Energy crops and raw grass biomass are both considered as industrial and energetic materials for future bio-refineries [71]. They can be used for methane production through anaerobic digestion and for the production of synthesis gas or bio-oil through pyrolysis or rapid pyrolysis, respectively. These biofuels are suitable for cogeneration plants or chemical industry [72]. Furthermore, they can be used for alternative fuels manufacture for idle diesel engines, ethanol and lactic acid production, saccharides, carotenoids and enzymes isolation [73].

One of the most used plants for energy purposes is *triticale,* which is a man-made species developed by crossing soft wheat (*Triticum* spp.) and rye (*Secale cereale* L.). *Triticale triticosecale* is an interesting crop for biofuel production, because it has huge potential for both grain and forage production [63–65]. The yield varies, between 8 and 16 tonnes dry matter/ha/year, according to the soil potential and the climate change, it is grown in regions with an annual average rainfall of 300–900 mm [75]. The starch content of triticale is about 60% and the ethanol yield is estimated to 380 L per tonne of dry matter [76].

As mentioned above, more than 32 million hectares of grazing lands are a real neglected fortune; these unused farmlands can be converted into fields to grow crops. These lands are very productive; located mainly in regions with a rainfall of 300–500 mm of water per year [77], they could provide between 256 and 512 Mt of dry matter, which represent 97,280 up to 194,560 million liter of ethanol, with an energetic potential of 49–98 Mtoe.

In addition to their energy importance, the environmental benefits from the use of energy crops include water and soil quality improvements, emission decreases at generation facilities, and wildlife habitat improvements (over traditional crops) [72], they even have a direct interest in soil remediation (phytoremediation) [78].

3 Bioconversion processes for bioethanol production

The feedstock composition and the structure influence the performance and the efficiency of both pretreatment and bioconversion steps. However, the general process remains the same; starting with a pretreatment operation to breakdown the polymeric units and increase the accessibility of monomeric sugar units constituting cellulose and hemicellulose, followed by the fermentation of the sugar solution to produce ethanol, and finally distillation to collect the pure alcohol.

3.1 The pre-treatment step

The pretreatment step for bio-ethanol production is estimated to account 33% of its total production cost [49–57]. The pretreatment aims at improving the production rate as well as the total yield of reducing sugars [68, 69]. But, it is important to notice that not all feed-stocks require the same pretreatment due to the variety of lignocellulosic composition [70, 71].

Table 1 Lignocellulosic biomass resources and energy potential

Biomass ressources	Tonne biomass/year	Tonne biomass/hectare	L ethanol/tons	Bio-ethanol production million liter/year	Energy estimation toe
Alfa	60,000	1–0.2	100	6.25	3150
Olive pomace	165,600	–	38	6.3	3500
Cereal straw	4,395,000	4.43	200–400	13.185	664,524
Corn straw	25,720	7.5–11	250–350	7.71	3888
Total	–	–	–	13.205	675,062

The overall effectiveness of the pretreatment process is correlated with a good balance between many conditions: The disruption level of the feedstock complex with the preservation of the hemicellulosic fraction, the production of microbial inhibitors, the high digestibility of substrates, the ability to recover high value-added molecules and also the amount of energy required for pretreatment [81]. Table 2 is a description of the most recommended pretreatment used for second generation bioethanol production.

3.2 Detoxification of inhibitory compounds

Since biomass conversion inhibitors can be problematic for various fermentative microorganisms and they reduce the yield and productivity of ethanol [82], the removal of inhibitory compounds from hydrolysates is typically necessary to facilitate the efficient microbial growth and fermentation [83]. However, the amount and the type of these inhibitory compounds depend upon the method of pretreatment and biomass materials utilized in the process [84, 85].

There are three main groups of inhibitors: organic acids, furan derivatives (furfural and 5-hydroxymethylfurfural (5-HMF)) and phenolic compounds [86]. Their effects vary widely among different strains of yeast and bacteria, furfural and HMF inhibit cell growth and ethanol production rates at lower concentrations [85]. For example, less than 10 mM of aldehyde inhibitors such as 4-hydroxybenzaldehyde, coniferyl aldehyde, syringaldehyde and vanillins is sufficient to inhibit the growth of the most yeast and bacterial strains [87–90]. On other hand, *S. cerevisiae* demonstrate dose-dependent cell growth and metabolic conversion activities in response to varied doses of HMF and/or furfural [91], 30 mM of these inhibitors is not enough to inhibit the yeast. However, 120 mM of only HMF is sufficient to inhibit the yeast and no cell growth is observed even after 128 h incubation [85]. The most commonly employed methods are physical, chemical, and biological in nature, although, the biological process is not recommended on a large scale. Among many techniques, the over-liming process is the most used; this technique reduces the levels of furans and phenolic compounds. It can be carried out with ammonia (NH_4OH), magnesium hydroxide ($Mg (OH)_2$), barium hydroxide ($Ba (OH)_2$), or sodium hydroxide (NaOH) [92–94]. It consists in increasing the pH of the hydrolyzate to 9–10 until obtaining a precipitate which will be subsequently eliminated; the pH can be adjusted again for the fermentation step [95].

Another technique to purify the hydrolyzates of their inhibitors is using anion exchange resins; this process may eliminate till 63% furans, 75% phenolic compounds and 85% acetic acid [96, 97]. Activated carbon is also effective for reducing furan and acetic acid concentrations [98]. Vacuum evaporation is another physical method that is used to reduce the amounts of volatile compounds present in different hydrolysates. Notably, the concentrations of furfural, vanillin, and acetic acid were reported to be significantly reduced from 29 to 100% following such evaporation treatment [97, 99, 100].

3.3 Hydrolysis and fermentation

The most widely used processes in bioethanol production are hydrolysis and separate fermentation (SHF), saccharification and simultaneous fermentation (SSF), saccharification and simultaneous co-fermentation (SSCF) as well as consolidated bioprocesses (CBP).

3.4 Hydrolysis and separate fermentation SHF

The cellulosic feedstock pretreatment is directly followed by the cellulose hydrolysis, contained in a solid phase of pretreated material. In this step, the polymers are transformed into fermentable sugars used subsequently by microorganisms in the fermentation process, using either acids or enzymes [101, 102]. Acid hydrolysis is considered the oldest and the most widely used method [103]. This method involves the use of dilute or concentrated acids. On the other hand, the enzymatic hydrolysis consists in using enzymes derived from microorganisms, more specifically fungi, such as *Trichoderma reesei* [104] and *Aspergillus niger* and/or bacteria such as *Clostridium cellulovorans* [105]. Overall, enzymatic hydrolysis is the most effective method for the release of simple sugars [60]. But the large amount of required enzymes for hydrolysis is one of the main challenges in the industrial production of bioethanol from lignocellulosic biomass [106, 107].

The liberated glucose (which is usually mixed with other hexose and/or pentose, according to the pretreatment method and the medium preparation) is then converted to ethanol by a selected microbial strain. The most widely used industrial microbial strains for a large-scale ethanol production are the yeast *Saccharomyces cerevisiae* and the bacterium *Zymomonas mobilis* [108, 109]. Although, this yeast is not able to consume pentoses naturally [110], metabolic engineering has been used to develop xylose-utilizing *S. cerevisiae* strains with the promise of an environmentally sustainable solution for the conversion of the biomass to ethanol [111–114].

In fact, these two consecutive operations are called separated hydrolysis and fermentation (SHF), and they are carried out in separate tanks, which is the main advantage of this method. Indeed, these two processes can be performed under optimum conditions (temperature, pH, nutrient composition, and solid load), since the optimum

Table 2 Pretreatment process for second generation bioethanol production

Pretreatment method	Process	Yield of fermentable sugars/hydrolysis efficiency examples	Inhibitor type and effect	Advantage	Disadvantage	Success at pilot scale	References
Physical							
Milling	Reduction of particle size with chipping, milling or grinding to increase surface/volume ratio	The released glucose reached 90% of the theoretical maximum after enzymatic treatment of milled wheat straw compared to 65% from reference samples after wet oxidation	No inhibitor formation	Reducing cellulose crystallinity, Green technique	Significant energy consumption 30 kWh per ton of biomass	Not recommended	[80–87]
Ultrasonic pre-treatment	Creating pressure differences within a solution for physical and chemical processes enhancement. This occurs at frequencies between 20 and 1000 kHz	The reaction rate of enzymatic hydrolysis of Carboxymethyl cellulose after 24 h increased by approximately 200% when treated with irradiation energy	No inhibitor formation	Short reaction time, maximum delignification, green technique, recommended for bioethanol production	High energy consumption 70.2 × 104 J/g	Yes	[85, 88–90]
Microwave irradiation	Interactions between microwaves and dielectric properties of the material. The electric field frequency is (2450 MHz) oscillates 4.9 × 109 times per second	The sugar yield was 12 times higher (75.3%) in the half of time compared with conventional treatment with 0.2 M H_2SO_4 for 20 min at 180° of *Miscanthus*	Low, acetic acid formation without effect	Acceleration of enzymatic hydrolysis, recommended for bioethanol production.	Significant energy consumption	Technology developed only at laboratory scale (TLS)	[85, 89, 89–96]
Pulsed electric fields (PEF)	The substrate is subjected to high voltages of 5–20 kv/cm for milliseconds. PEF creates pores in cell membranes, to allow the appropriate agents to break down cellulose into free sugars	Application of PEF for the pretreatment of wood chips and switch grass. And found to be effective in increasing the tissues porosity	No inhibitor formation	Create damage in the plant tissue, processing at normal temperatures and pressure, low energy	Average extraction of sugars	TLS	[97, 98]

Table 2 (continued)

Pretreatment method	Process	Yield of fermentable sugars/hydrolysis efficiency examples	Inhibitor type and effect	Advantage	Disadvantage	Success at pilot scale	References
Physico-chemical							
Steam-explosion	High pressure saturated steam injection to the biomass. The explosion of steam is initiated at 160–260 °C (corresponding pressure of 0.69–4.83 MPa) for a few seconds to a few minutes before the reduction of the pressure	90% efficiency of enzymatic hydrolysis is achieved in 24 h for poplar chips pretreated by steam explosion, compared to only 15% hydrolysis of reference samples	High; Coniferyl aldehyde and formaldehyde	Improvement of hydrolysis, extraction of hemicelluloses, green technique, less expensive, recommended for bioethanol production	Incomplete breakdown of lignin	Yes	[84, 91, 99–104]
Liquid hot water	Performed in two steps: The biomass is exposed to a temperature of 230 °C and a pressure of 10 MPa for 15 min; then with a higher temperature 275 °C	Between 40 and 60% of the total biomass is dissolved (4–22% of the cellulose, 35–60% of the lignin and all of the hemicellulose is removed)	Low; acetic acid, minor amounts of furan aldehydes	Improvement of hydrolysis, maximum sugars recovery, low temperature requirements, recommended for bioethanol production	Hight energy and water consumption	Yes	[105–114]
Ammonia fiber explosion (AFEX)	Treating the materials with liquid anhydrous ammonia (1–2 kg of ammonia/kg of dry biomass) at 90 °C in 30 min as a residence time	66% of lignin solubilization and saccharification yields of 83% for glucan and 63% for xylan when treating destarched barley hull with 15% aqueous ammonia	No inhibitor formation	Low overall cost, improved hydrolysis, ammonia recycling, the small particle size is not necessary, low cost process; no additional measures (washing and detoxification)	Less effective on materials rich in lignin, less recommended for bioethanol production.	–	[80, 85, 91, 115–119]
Carbon dioxide explosion CO_2	The cellulosic materials are placed in a reactor under pressurized carbon dioxide at 35 °C for a controlled time period upon an explosive release of the carbon dioxide pressure	75% of released glucose was obtained after 24 h from enzymatic hydrolysis of pretreated alfalfa	Very low; phenolics and furan derivatives formation	Hemicellulose solubilization, decrystallization of cellulose	High energy consumption, no effect on lignin	–	[79, 92, 120–122]

Table 2 (continued)

Pretreatment method	Process	Yield of fermentable sugars/hydrolysis efficiency examples	Inhibitor type and effect	Advantage	Disadvantage	Success at pilot scale	References
Chemical							
Diluted acid	Performed into two different conditions; a high temperature above 160 °C in continuous mode for a low loading of solid materials, and a temperature below 160 °C in batch mode for solid materials high loading. The structure of lignocellulosic material is cracked, and then followed by the elimination of hemicelluloses	85% glucose and 91.4% xylose yields was achieved after 10 min of pretreatment with diluted phosphoric acid of corn stover	High; acetic acid, formic acid, levulinic acid, furfural, 5-hydroxymethylfurfural (HMF) formation	High solubility of hemicellulose and alteration of lignin, recovery of sugars without the need for subsequent enzymatic hydrolysis	Recovery of used acids is expensive, require equipment that resist corrosion; lignin is not completely removed from biomass, less recommended for bioethanol production	–	[123–132]
Strong acid	It consists in using concentrated sulfuric acid (65–86% w/v), hydrochloric acid (41%) or phosphoric acid (85% w/w), to pretreat dried (5–10% moisture), pulverized biomass at low temperatures (30–60 °C) and pressures	Approximately 100% of cellulose is converted to glucose	High; furfural and HMF formation	Hydrolysis of cellulose and hemicelluloses, alteration of lignin, recovery of sugars without enzymatic hydrolysis, recommended for bioethanol production	Toxic, dangerous and require reactors that resist corrosion, the concentrated acid must be recovered to make the process economic.	Yes	[84, 124, 126, 133–135]
Sodium hydroxide	Dilute solution of 0.5–2.5% sodium hydroxide at 120 °C is used. After 120 min the solid biomass is separated, washed with distilled water, and dried	Delignification of 65.6% and 60.8% of cellulose conversion after 90 min at 121 °C/15 psi when pretreated with 2% NaOH	Low; acetic acid, hydroxy acids, dicarboxylic acids, phenolic compounds	Disturbance of lignin structure, reduction of cellulose crystallinity	High cost of acid	Yes	[96, 108, 124, 133, 136]

Table 2 (continued)

Pretreatment method	Process	Yield of fermentable sugars/hydrolysis efficiency examples	Inhibitor type and effect	Advantage	Disadvantage	Success at pilot scale	References
The green solvent (Ionic liquid)	These organic salts are composed of ions and exist in the liquid state, usually melt below 100 °C. The reactions can be applied in mild conditions and they can be reused after the process	High glucose (> 80%) and xylose yields (52.2%) can be achieved in the treatment process of rice straw with amino acids	Dependent on solvent and conditions	Respectful of the environment, requires less energy, recommended for bioethanol production	High cost of green liquid, regeneration requirements, lack of toxicological data, unknown mechanism of action on hemicellulose and/or lignin	TLS	[92, 108, 137–139]
Natural deep eutectic solvents NADES	The biomass is treated with NADES in appropriate reaction vessel and incubated at 60 °C for 12 h with constant agitation at 100 rpm	60 ± 5% of high purity lignin could be removed from the biomass residue using NADES treatment of rice straw	No inhibitor formation	Moderate solvent cost, non-toxic, highly biodegradable, recovery and possible reuse, maximum delignification, no requirement of the detoxification, reduced cost	New technique, limited number of biotechnological studies	TLS	[85, 140]

temperature of each process differs considerably [109, 115–117]. However, the contamination problem is prone to this process.

3.5 Simultaneous saccharification and fermentation (SSF)

Saccharification and simultaneous fermentation (SSF) is a process that combines the two major steps of bioethanol production; sugar hydrolysis and fermentation in a single bioreactor, where two organisms are co-cultured together in the same vessel [118]. It has been found that the yield of bioethanol produced is higher than that obtained with the previous process SHF [119, 120]. The monomers of sugars released in the hydrolysis step are directly fermented into ethanol, except that in the SSF process only hexoses are converted into ethanol, as for pentoses, they can be fermented separately in another vessel with a different microorganism [82]. Indeed, the principal benefits of SSF are the reduced enzyme inhibition, the smaller amounts of enzymes, the investment costs, sugar accumulation and contamination problems can be avoided in this process [116, 120–122]. Indeed, the optimization of substrate and enzyme concentration, pH and temperature are important to optimize the ethanol yield [123].

On the other hand, most yeasts have an optimal temperature around 30–35 °C, while the optimal activities of hydrolyzing enzymes is around 50 °C [136]. Whereas, a compromise must be found to develop the best strategy that ensure optimal conditions for both enzymatic hydrolysis and fermentation. For this reason, several thermo-tolerant bacteria and yeasts, e.g. *Candida acidothermophilum and Kluyveromyces marxianus* have been proposed for their use in the SSF [124–127].

3.6 Simultaneous co-fermentation and saccharification (SSCF)

Unlike SSF, the enzymatic hydrolysis can be performed simultaneously with the co-fermentation of hexose and pentose in the simultaneous co-fermentation and saccharification (SSCF) process [128, 129]. Therefore, a single fermentation step is required to treat the hydrolysed sugar mixed fractions of the pretreated biomass in a single vessel [130, 131].

The major advantages of this process include, the continued removal of cellulases or β-glucosidases inhibitors [132] the reduced capital cost [133] and a higher productivity of ethanol yield than that obtained with SHF [57, 88]. However, a limited number of bacteria, yeasts and fungi that can convert derived sugars from hemicellulose into ethanol with satisfactory yield and productivity is recognized [60]. The concept of metabolic engineering has been used recently for an efficient fermentation of mixed sugars. Certain recombinant bacteria and yeasts, such as *Z. mobilis* [129, 131, 135], *E. coli* [136], and *S. cerevisiae* [110, 128, 137, 138] etc., have shown promising results and they are being considered for commercial scaling up.

3.7 Consolidated bioprocess (CBP)

Consolidated bioprocessing (CBP) of cellulosic feedstock for G2BP using a single organism combines saccharolytic enzyme production, polyaccharides hydrolysis to simple sugars and both hexose and pentose monomers fermentation into a one-step process in the same vessel [139, 140]. However, this process has not yet been used on a commercial scale for G2BP [141], an ideal cellulase production host system and the co-use of xylose–glucose is not yet well established [137].

Two potential pathways have been identified for obtaining an effective engineered microorganism that can be used in CBP technology. The first process involves the production of ethanol by naturally cellulolytic producers such as *Trichodermareesei*, *Clostridium* sp., and *Bacillus subtilis.* The second pathway is the production of cellulase by naturally fermentative organisms such as *S. cerevisiae, Pichia stipitis* and *Kluyveromyces marxianus* [142, 143].

Den Haan et al. [144] developed a recombinant strain of *S. cerevisiae* that can be used for CBP. Two genes encoding cellulose, an endoglucanase from *T. reesei,* and β-glucosidase from *Saccharomycopsisfibuligera*, in combination, were expressed in *S. cerevisiae*. The resulting strain was able to grow on cellulose by a simultaneous production of extracellular endoglucanase and a sufficient β-glucosidase. Briefly, they demonstrated the construction of a yeast strain capable of growing and converting cellulose into ethanol in a single step. Another recent study by Lee et al. [137] of the production of bioethanol from rice straw by one-pot fermentation of recombinant *S. cerevisiae* strain secreting different cellulases, using a cells mixture that secrete cellulases and produce ethanol. These studies represent a significant progress towards achieving a one-step treatment of lignocellulose in a CBP configuration.

3.8 Distillation

Although this downstream process is energy-intensive [145, 146] and requires very high amounts of steam [81], the recovery of ethanol from fermented broth is necessary. The costs of distillation depend on the efficiency of enzymatic hydrolysis and the fermentation, and they increase with low produced concentrations of ethanol [147–149]. The recovery of ethanol starts with an ordinary distillation (OD); about 92.4–95% of ethanol is firstly obtained from the dilute aqueous solution, and to reach 99.9% anhydrous

Table 3 A summary of bioethanol distillation methods

Distillation method	Process	Advantages	Disadvantages
Ordinary distillation (OD)	Separation based on the difference in boiling temperatures of the components or their volatilities; pre-concentrator column, is used to concentrate dilute ethanol to 92.4 wt%	Simple process, no special requirements	Not economical
Azeotropic distillation (AD)	Addition of a third volatile component (entrainer) which changes volatilities and alters separation; two distillation columns are used, a dehydration column and entrainer recovery column	Simple and efficient	High energy consumption, large capital cost, health and safety concerns
Extractive distillation	Addition of a third component to increase the relative volatility and separation of the components using high boiling solvent such as ionic liquid, dissolved salt, volatile liquid solvent and dissolved salt mixture, or hyperbranched polymer	Less energy requirements than AD, low energy assumption, environment-friendly process and no safety and health hazards when using dissolved salt and ILs	Complex process and availability of solvents and suitable salts, possible contaminations
Liquid–liquid extraction-fermentation hybrid	In situ extraction using a high efficient and non-toxic to microorganism solvent for the recovery of anhydrous ethanol from the aqueous fermentation broth	Low energy assumption, increase ethanol yield, reduction in fresh water consumption	Substantial expertise when it comes to biocompatible extracting agents
Adsorption	Liquid-phase adsorption and vapor-phase adsorption of water from the fermentation mixtures using bio-based or molecular adsorbents	Low energy demand	Low separation capacity for bio- based adsorbents than molecular sieves, expensive molecular sieves
Membrane separation	Solution–diffusion mechanism in membrane pervaporation PV using inorganic, polymeric or composite membrane; it can be either vacuum PV or sweep gas PV using an inert sweep gas such as N2	Most effective, energy saving process	Expensive set-up and sieves

ethanol which can be added to gasoline [150], additional dehydration is required by employing several methods which are capable to separate close boiling mixtures from the OD [98, 151]. On the other hand, many researchers proposed several new economical processes to overcome this problem, including heat integrated, membrane-based, feed-splitting, and ohmic-assisted distillation methods. However, further in-depth studies of the sustainability and the exact energy demands of these techniques are required [152]. A succinct summary of the mentioned ethanol recovery methods is described [98, 152, 153] in Table 3.

4 Conclusion

A maximized use of natural resources is the advisable strategy that makes economic, ecological and logistical sense for Algeria. This allows agrarian populations to meet their energy needs more autonomously. Indeed, agricultural straw is not very available as an energy resource for bioethanol production in Algeria because of other uses. But untapped Alfa populations and olive pomace are a very important source of renewable bioenergy to be considered as raw material.

The conversion of lignocellulosic biomass to bioethanol depends on their nature and abundance in the environment and also on the choice of their pretreatment process. The successful choice of methods for biomass bioconversion into ethanol could be a leap forward in low-cost conversion of renewable biomass to fuels, as well as a variety of industrial chemicals, realizing huge societal benefits as well. The strong acid pretreatment is the most effective and used process to hydrolyze lignocellulosic straw including wheat, corn, and triticale straw, even Alfa fibers and olive pomace to fermentable sugars. Therefore, subsequent enzymatic hydrolysis step is sometimes not required which reduces the overall process cost. However, a detoxification step is sometimes required to remove the inhibitors that reduce the effectiveness of fermentation step.

If the only studied resources in this report are considered, a potential of 0.67 Mtoe can be reached from lignocellulosic materials which represents almost 4.37% of energy consumption of transport sector in Algeria, which reached 15.3 Mtoe in 2018 [23]. On the other hand, dedicated cereal could generate up to 90 million tonnes of ethanol with an energetic potential of 57.9 Mtoe. Energy crops are another very eminent theoretical point; 118.51 million tonnes that could be produced from these crops, with an energetic potential of 73.5 Mtoe which represents more than the national energy consumption which reached 60.96 million toe in 2018 [23].

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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