Conversion of biomass-generated syngas into next-generation liquid transport fuels through microbial intervention: potential and current status

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The production of biofuels from synthesis gas that utilizes a wide variety of biomass is an emerging concept, particularly with the focus on biomass-based economy. Biomass is converted to synthesis gas via gasification, which involves partial oxidation of the biomass at high temperature. This route of ethanol or liquid biofuel production has the advantage of utilizing the entire biomass, including the lignin content. Though the technology is yet to be established, there is a major breakthrough in understanding the microbial route of synthesis gas conversion. Acetogenic microorganisms such as *Clostridium ljungdahlii*, *Clostridium aceticum*, *Acetobacterium woodii*, *Clostridium carboxidivorans* and *Clostridium autoethanogenum* have already been reported to play a role in the conversion of synthesis gas to ethanol and acetic acid. Poor mass transfer properties of the gaseous substrates and low ethanol yield from these biocatalysts are the major challenges, preventing the commercialization of synthesis gas fermentation technology. This article reviews the existing literature on biomass-derived synthesis gas fermentation into biofuels, specifically ethanol. Special emphasis has been laid on understanding the need of synthesis gas fermentation and its bioconversion into next-generation liquid transport fuels. However, advantages of microbial process over conventional methods and the role of different microorganisms and pathways used have also been described. The article also outlines the challenges and future research directions regarding up scaling and commercialization of synthesis gas fermentation technology.

Keywords: Biomass, microbial interventions, synthesis gas, transport fuels.

Current methods and sources for production of transport fuels

The society we are living in is facing a rise in oil prices and increased global warming threats because of intensive use of conventional fossil fuels such as coal and crude oil. In developing countries, 30% of the energy demand is from the transportation sector, 90% of which depends upon fossil fuels. The emphasis on alternative and sustainable fuel resources has gained importance due to the presumed fear of fossil fuels shortage in the future and the resultant environmental threats, particularly in terms of CO_2 emissions[1,2]. However, currently transport fuels are commercially produced from sugar, starch and oilseed-based feedstock. For example, bioethanol is produced from cornstarch in the United States, cassava starch in Thailand[3] and cane sugar in Brazil[4]. Moreover, soybean, palm fruits, rape and canola seeds are also the common feedstock for biodiesel production[5]. There is rising concern that biofuels produced from food sources would affect their availability by increasing the cost of food crops and also the food versus feed problem.

Therefore, biofuels produced from synthesis gas (mainly a mixture of CO, CO_2 and H_2) can be considered as a possible alternative to reduce the dependency on fossil fuels and their effects on greenhouse gases (GHGs). The most desirable biofuel that can be produced from synthesis gas is ethanol, which is being used as an additive in conventional transport fuel (gasoline)[2]. Syn(thesis)gas can be derived from various raw materials such as coal, lignocellulosic biomass, plant waste material, rice husk, municipal sewage waste, etc. and then converted into transport fuel through microbial interventions.

Current scenario regarding demand and availability of transport biofuels

The world's total demand of oil, natural gas and coal reserves is 168.6 billion tonnes, 177.4 trillion cubic metres, and 847.5 billion tonnes respectively by the end of 2007. In 2007, world oil production was 3.90 billion tonnes, a decrease of 0.2% from 2006. According to the International Energy Agency, the transportation sector accounts for approximately 60% of the world's total oil consumption. South America and Brazil already have policies that

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mandate at least 22% bio-ethanol on motor fuels and encourage the use of vehicles that use hydrous bioethanol[6]. Biofuels have gained considerable attention because of the relative abundance of feedstock in all regions, easy utilization of biofuels in combustion engines and compatibility with existing fuel distribution infrastructure. They can also provide a new end market for agricultural commodities, thereby revitalizing rural areas. The first significant large-scale momentum for the production and use of biofuels occurred in Brazil and the US, as a response to the 1973 oil export embargo imposed by the Arab members of OPEC (Organization of the Petroleum Exporting Countries) against Japan, the US and western European countries[7]. Currently, biofuels are once again the centre of attention for the debate on energy, partially in response to those circumstances that occurred more than 30 years ago, namely high oil prices and oil supply insecurity. In addition, a strong global consensus currently advocates for reduction in GHG emissions as a crucial step to combat rising global temperatures. Nowadays, government agencies are also promoting research on the aspects of biofuel production to control emissions of harmful and toxic gases.

Need of generating second-generation liquid fuels for developed and developing countries

Current global concern about fossil fuel prices and availability, has increased the interest of many developed and developing countries, including India for energy independence and the need to reduce GHG emissions. India is the second largest producer of sugar, as the country's agricultural and rural economy is mainly dependent on sugarcane farming and related industries. The hard currency savings benefit from the use of fuel will be substantial even if one considers blending it with gasoline at the rate of 5% or 10%. Ethanol is mainly produced from the sugarcane molasses and also from a variety of renewable agricultural feedstock, including grains such as corn, wheat, sorghum, rice and millets. The use of ethanol for applications such as blending with petrol, production of downstream industrial chemicals and beverage will offer great feasibility, stability and diversity in the agricultural and energy sector. Typically for the Indian scenario, bioethanol affects seven major national issues of sustainability, global climate change, biodegradability, urban air pollution, carbon sequestration, national security and agricultural economy. Lignocellulosic biomass is proposed to provide a significant portion of the raw materials for biofuel production due to low cost and high availability[6]. The fuel prices are expected to remain high in the coming years due to increasing demand for ethanol. It has become difficult for liquor manufacturing units to purchase good-quality alcohol from the open market and run them economically. Another well-established route for the manufacture of portable alcohol and fuel ethanol is using grains as feedstock. However, considering the increase in demand as a food source and the rising prices, the availability and feasibility of using food grains as feedstock is doubtful. Further expansion of ethanol production from the feedstock, thus triggers a debate on food/feed versus fuel, limiting the use of first-generation feedstock for fuel ethanol production. Thus, for sustainable fuel-grade ethanol production, non-food feedstock such as lignocellulose raw material should be used[1]. Therefore, it shows the urgency for development of second-generation biofuels.

Bio-based liquid transport fuel

First- and second-generation transport fuel

First-generation biofuels refer to the fuel produced from food crops such as sugar cane, soya bean and other food-based feedstock. These biofuels are in the market in considerable amount today and their production technologies, in spite of ongoing improvements, are well established. The most important first-generation biofuels are bioethanol, biodiesel and biogas[7].

Second-generation fuels are derived from nonedible lignocellulosic (LC) biomass. These are either residues of forest management or food crop production (e.g. corn stalk or rice husk), or whole plant biomass (e.g. grasses or trees grown specifically for biofuel purposes). Lignocellulosic biomass such as agricultural residues (e.g. corn stover, wheat and barley straws), agri-processing by-products (e.g. corn fibre, sugarcane bagasse, etc.) and energy crops (e.g. switch grass, poplar, red grass, etc.) does not compete with food and feed, and is considered to be renewable feedstock for ethanol production[8]. This can be grown specifically for energy purposes and represents more of the plant material, thereby further increasing land-use efficiency. These features of lignocellulosic biomass can help substantially in meeting the fuel demands with environmental benefits. Though considerable amount of investment has gone into this sector, major breakthroughs are awaited for the current bottlenecks, particularly in conversion efficiency. Figure 1 provides an overview of the process for the generation of biofuels.

Third-generation transport fuel

Among the third-generation biofuels, the focus is on thermochemical conversion of lignocellulosic biomass to synthesis gas which is further biologically fermented to biofuel. In this route, lignocellulose biomass feed stocks from agriculture, forests or municipal waste with the help of partial oxidation (gasification at higher temperature) is converted to syngas, and then syngas (after removal of some contaminants) can be further used for conversion to liquid fuels. The conversion of syngas to

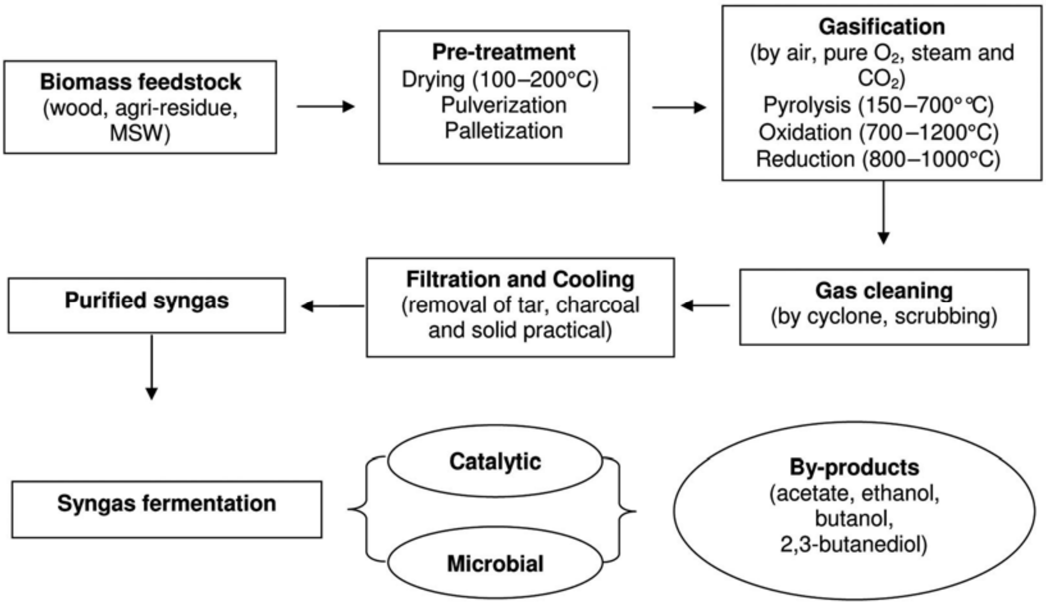

Figure 1. Schematic representation of syngas bioconversion process to platform chemicals.

biofuel is primarily achieved through two methods: catalytic method and microbial fermentation. Breakdown of lignin content into carbonaceous compounds is of significance in third-generation transport biofuels[2,8]. Government agencies around the world have recognized the role of biofuels in the renewable fuels portfolio and have also introduced minimum targets for their implementation in the future. Strategic focus and prioritizing a mode that can augment the existing efforts in addition to circumventing few of the present drawbacks of second-generation protocols is urgently required.

Synthesis gas to liquid transport fuels

Synthesis gas and its conventional application

Syngas mixture mainly depends on the process of gasification and feedstock used. The gasification process involves three steps – pre-treatment of feedstock (drying), gasification and pyrolysis at higher temperature (300–500°C). Most gasifiers used in industry and research are moving towards bed fluidized bed and entrained flow gasifers[11]. After gasification, the syngas mixture is passed through a series of filters to remove unwanted pollutants such as tar and solid particles. Anaerobic microbes can utilize the mixture of syngas as a carbon and energy source to produce alcohols (e.g. ethanol or butanol) and organic acids (e.g. acetate or butyrate)[12].

Syngas-derived liquid transport fuel

World energy consumption of unsustainable oil, coal and natural gas is estimated to increase up to 44% in the coming 20 years. Syngas from biomass feedstock has been identified as a sustainable alternative for growing energy demands and has several advantages such as a higher availability of biomass, no competition with food and low feedstock cost[9]. Therefore, production of liquid biofuel from syngas is an emerging concept that can utilize a wide variety of biomass. Fuel-grade ethanol and other valuable commercial products have remarkable growth in the fuel industry due to the increasing demand for renewable sources.

Advantages of using syngas

Syngas fermentation has many fundamental advantages over first-generation and second-generation technologies. The main advantages of conversion of syngas to biofuel are: (i) The production of beneficial products from waste materials which need to be discarded in landfills or oceans[13]. (ii) Generation of syngas from plant biomass gasification is another promising concept, indicating that any carbon-based material can be gasified to produce syngas. (iii) Carbon monoxide and carbon dioxide are released during the conversion of biomass to syngas. Approximately all the carbon in the biomass, including the lignin content is converted to syngas[14]. (iv) This makes the syngas conversion process an efficient energy producer and an environmental-friendly concept for the recycling of waste biomass.

Conventional methods of syngas bioconversion

Thermochemical conversion transforms the lignocellulosic feedstock into a mixture of carbon monoxide, hydrogen and carbon dioxide (also called syngas) by partial combustion of biomass. These gases can be converted to liquid transportation fuels or chemicals by chemical catalytic or microbial routes.

Chemical catalytic method

Fischer–Tropsch (FT) method is employed to convert syngas components (CO, CO_2 and H_2) using metal catalyst[15]. Syngas can be introduced to a catalytic reactor where carbon monoxide and water are combined via a metal catalysed process to produce ethanol, higher alcohols and liquid fuels. FT reactions generally produce hydrocarbons of different lengths, which can be further used for the production of conventional diesel, kerosene and gasoline. FT synthesis includes cobalt, copper, ferrous, aluminum, zinc, molybdenum, nickel, rubidium and ruthenium as catalyst[16].

Drawbacks and challenges of chemical catalytic method

Major pitfalls in FT synthesis are the high cost of catalysts, fixed H_2/CO ratio, catalyst poisoning due to toxic gases, sulphur contaminants together with high operating parameters like temperature and pressure. (i) Sulphur contaminants found in the synthesis gas, primarily hydrogen sulphide (H_2S) and carbonyl sulphide $(COS)_2$ are potent catalyst poisons. These gases must be removed in energy-intensive purification steps that add significantly to the product cost. (ii) Catalytic processing of synthesis gas often requires strict CO/H_2 ratios to maintain a particular product mix, necessitating gas recompression and shift reaction conversion operations. (iii) The gas-phase reactors operate at high temperature, pressure and under extreme conditions, thus increasing reactor cost as well as potential safety issues. (iv) In addition, the product specificity of the catalysts is often poor, resulting in a broad product spectrum[12,17,18].

Microbial method and its application

The conversion of biomass-derived synthesis gas into biofuels by microbial catalysts such as *Clostridium ljungdahlii*, *Clostridium autoethanogenum*, *Acetobacterium woodii*, *Clostridium carboxidivorans* and *Peptostreptococcus productus* has gained considerable attention as a promising alternative for biofuel production in the recent past. The syngas fermentation into ethanol and other by-products is considered to be more attractive due to several inherent merits over the biochemical approach and the FT process[28,39] such as: (i) Utilization of the whole biomass, including lignin irrespective of the biomass quality. (ii) Elimination of complex pretreatment steps and costly enzymes. (iii) Higher specificity of the biocatalysts. (iv) Independence of the $H_2:CO$ ratio for bioconversion. (v) Aseptic operation of syngas fermentation due to gasification at higher temperature. (vi) Bioreactor operation at ambient conditions. (vii) No issue of noble metal poisoning.

Microbiology of syngas fermentation

The gasification of biomass to produce syngas followed by anaerobic fermentation is an alternative to produce biofuel and energy, and thus reduction in the stress on fossil fuels. Several acetogenic microorganisms have been isolated which have the ability to ferment synthesis gas to ethanol, acetic acid and other useful by-products. Microbial production of acetate, format, butyrate, ethanol, butanol and hydrogen has immense use in the industry[22]. *C. ljungdahlii* and *C. autoethanogenum* were reported as the first organisms utilizing CO, CO_2 and H_2 for ethanol and acetic acid production[18,23]. These microbes have the ability to reduce CO_2 to acetate using the acetyl-CoA pathway as their predominant mechanism to obtain energy, for cell growth and for producing essential by-products. They are obligate anaerobes and may be Gram-positive or Gram-negative, rod-shaped or coccoid, and motile or non-motile. As a versatile group of microorganisms; they can also use sugars and other substrates along with gases like CO_2/H_2 and CO[24,25].

Wood–Ljungdahl pathway and its biochemistry

Autotrophic syngas utilizing anaerobic bacteria depends upon the acetyl-CoA pathway for cell growth and product formation. Under strict anaerobic conditions, acetogens and sulphate-reducing bacteria use this pathway for the production of acetate, butyrate, ethanol and butanol from syngas fermentation. This pathway was first described by Wood and Ljungdahl in 1986 and therefore is named as the Wood–Ljungdahl pathway[26]. This pathway contains two branches – eastern and western. The eastern branch involves reductive steps to convert CO_2 to methyl group of acetyl-CoA by reducing six electrons. The western branch generates CO from CO_2 or directly takes CO which acts as a carbonyl group for the acetyl-CoA.

The overall reductive acetyl-CoA pathway is an irreversible, non-cyclic pathway occurring under strict anaerobic environment. There are two major steps involved in the production of acetyl-CoA. During the first step, CO or CO_2 is reduced to a methyl group through a series of reductive reactions in the presence of hydrofolate-dependent enzymes and at the expense of ATP. In the second step, the methyl, carbonyl and CoA groups are combined by the enzymes acetyl-CoA synthase (ACS) and carbon monoxide dehydrogenase complex (CODH) to produce acetyl-CoA[14]. Acetyl-CoA is further reduced to acetate, ethanol and other by-products during the later stages of the pathway. Acetyl-CoA serves as a precursor for cell macromolecules as well as a source for adenosine triphosphate (ATP) synthesis. Syngas-fermenting microorganisms use the acetyl-CoA pathway to produce ethanol, acetic acid and other by-products such as butanol and butyrate from syngas. Acetate and ATP are generated in the growth phase and ethanol is generated in the non-growth phase.

Microbial strains producing ethanol from syngas

One of the most revolutionary biofuels having high octane number and that can replace the present fossil fuels is ethanol. Recognized as an alternative fuel, ethanol is an oxygenated, water-free additive to gasoline. As an additive it can substitute MTBE (methyl tertiary butyl ether), which is used as oxygenate and also eliminate groundwater pollution and burn cleaner than petroleum.

In 1987 the first Gram-positive, rod-shaped, autotrophic, acetogenic anaerobic bacterium *C. ljungdahlii* was isolated, which is capable of fermenting syngas to ethanol. *C. ljungdahlii* also has the ability to ferment sugars like xylose and fructose in addition to synthesis gas[28].

Eubacterium limosum is an acetogen which has been isolated from various habitats like the human intestine, rumen, sewage, soil. It has high growth rate under high CO concentration producing acetate, ethanol, butyrate and isobutyrate[33].

C. autoethanogenum is strict anaerobic, Gram-positive, spore-forming, rod-like, motile bacterium reported to produce ethanol, acetate and CO_2 as end-products from CO and CO_2. It is also capable of using CO_2 and H_2, pyruvate, xylose, arabinose, fructose, rhamnose and L-glutamate as substrates[23].

C. carboxidivorans P7T is another novel solvent-producing anaerobic bacterium, isolated from the sediment of an agricultural settling lagoon forming acetate, ethanol, butyrate and butanol as end-products[30]. Table 1 provides further information regarding syngas fermenting bacteria, their optimum pH and metabolites produced, as well as other characteristics.

Challenges and future research direction for syngas fermentation

Mass transfer

The major challenge in the commercialization of syngas fermentation technology is the gas-to-liquid mass transfer limitation due to the low solubility of synthesis gas components, i.e. CO, CO_2 and H_2 in liquid medium. Moreover, solubility of CO and H_2 in water is only 77% and 65% respectively, with respect to oxygen[32]. Due to the low diffusion rate, lesser availability of gases as substrate to the microorganisms results in low product yield. Therefore, the bubble diameter plays an important role in gas-to-liquid mass transfer, leading to the use of micro-bubble dispersers. In mass transfer limited condition, the bubble diameter is inversely proportional to the specific surface area[33]. However, mass transfer in case of gas-to-liquid fermentation is measured in the terms of volumetric mass transfer coefficient (kLa). To improve the mass transfer limitations there is a need of advancement in the current methods of reactor design such as impeller designs, fluid-flow patterns, aerated power efficiency, mixing time and baffle design. Gas-to-liquid mass transfer is a rate-limiting step in syngas fermentation process. Use of hollow fibre membrane and nanoparticles is another innovative approach to enhance the mass transfer rate over conventional reactor configurations[34–36]. The mass transfer coefficient (kL) (m/s) for a slightly soluble gaseous substrate can be determined using eq. (1)[28]

$$1/V_L \mathrm{d}NG_S/\mathrm{d}t = KL_S/H(PG_S - PL_S), \tag{1}$$

where NG_S is the molar substrate transferred from the gas phase, $V_L(L)$ the reactor volume, PG_S and PL_S (atm) are the partial pressures of the gas in gas and liquid phase, H (L atm/mol) is the Henry's law constant and (m^2/L) is the gas–liquid interface surface area for unit volume. The difference in the partial pressures of the gases is the driving force for mass transfer and thus controls the solubility of the gaseous substrate. High pressure improves the solubility of the gas in aqueous phase.

Earlier studies observed mass transfer using different bioreactor configurations. The most common strategy for improving the mass transfer in CSTRs is by increasing the agitation speed of the impeller[32,37]. However, by implementing this approach it is possible to obtain smaller bubbles size, thus increasing the gas–liquid interfacial area for efficient mass transfer. Subsequently, other reactor configurations such as trickling bed reactors, air-lift reactors and bubble column reactors have been tested for efficient mass transfer. The mass transfer rates between stirred-tank and bubble column reactors was compared by Bouaifi *et al.*[32]. It was found that the kLa obtained for the bubble column reactor was higher than that of the stirred-tank reactor. Another study reported the hydrodynamic and mass transfer properties of micro-bubble dispersions in a bubble column reactor[39]. Previous studies showed that the axial mixing of the micro-bubble dispersion was considerably less than that of the conventional bubble column reactors.

Syngas quality

Syngas is a mixture of CO, CO_2, H_2 and traces of other impurities such as tar, ash, ethylene, ethane, acetylene

Table 1. Comparison of ethanol yield by different mesophilic syngas fermenting bacterial strains[45]

Microbial species	T_{opt} (°C)	pH_{opt}	EtOH yield (g/l)	Products	Reference
Clostridium ljungdahlii	37	n.a	0.6	Acetate, ethanol	42
Clostridium autoethanogenum	37	5.8–6.0	0.32	Acetate, ethanol	23
Clostridium ljungdahlii	37	4.0–5.0	1.0	Acetate, ethanol	46
Clostridium carboxidivorans $P7^T$	37	5.8–5.9	0.56	Acetate, ethanol, butanol	41
Clostridium ragsdalei	32	6.0	1.89	Acetate, ethanol	47
Butyribacterium methylotropphicum	37	6.0	N.A	Acetate, ethanol, butanol	31
Eubacterium limosum	38–39	7.0–7.2	N.A	Acetate, ethanol	29
Peptostreptococcus productus	37	7.0	N.A	Acetate, ethanol	49
A. bacchi	37	5.8–7.0	1.7	Acetate, ethanol	48
Mixed culture TERI SA1	37	6.0	2.3	Acetate, ethanol	45

and gases containing sulphur (SO_x) and nitrogen (NO_x). Syngas utilizing bacteria generally use CO, CO_2 and H_2 for their growth and production. Due to the trace amount of impurities, the biomass-generated syngas sometimes has problems regarding culture stability and carbon conversion efficiency inhibiting hydrogenase activity. Syngas should be cleaned before being introduced into the fermentation process. Pyrolysis of biomass also releases tar, which affects microbial activity in syngas fermentation. Almost 90% of tar particles can be converted into syngas using light hydrocarbons[10]. It has been observed that cell dormancy and product redistribution are most likely caused by tar present in syngas[38]. Several gas clean-up methods are currently available for syngas fermentation, including mechanical methods such as cyclones, fabric, ceramic and bag filters, rotating particle separators, water scrubbers and wet electrostatic precipitators[39]. Using appropriate gasification and these preprocessing techniques, impurities can be reduced up to some extent. This technique has been successfully analysed for sugarcane family feedstock to reduce nitrogen and sulphur containing compounds[40].

Microbial catalyst

The selection of appropriate microorganisms for efficient syngas fermentation is a challenging task. Strict mesophilic anaerobes such as *C. ljungdahlii*, *C. aceticum*, *A. woodii*, *C. autoethanogenum* and *C. carboxydivrons* are frequently being used in syngas fermentation[28,41,42]. In addition, the isolation and engineering of new microbial species, which are more productive and robust, need to be developed. For commercialization of the process, isolation of anaerobic microorganisms capable of converting syngas into ethanol and other by-products with higher productivity is another important aspect. Isolation of less-sensitive syngas-utilizing thermophiles which can convert CO into ethanol or butanol might be an interesting area to study. On the other hand, to produce high-yielding genetically modified syngas-fermenting microbes is another important challenge[30].

Product recovery

The low microbial resistance to liquid biofuel (mainly ethanol) in the fermentation broth is another major hindrance in developing this technology. Fermentation broth also contains dissolved and undissolved compounds (cell extracts and unfermented soluble compounds), which create separation problems during recovery. Thereby *in situ* separation is considered a better choice by coupling the fermented vessel with various unit operations[10]. Ultrasonic atomization, vapour recompression, vapour reuse and vacuum distillation and selective adsorption of water are some of the alternative methods that have been examined in order to reduce the ethanol recovery cost[43]. Liquid–liquid extraction is a widely used separation technique for acetic acid recovery.

Redirection of metabolic pathway

Metabolic engineering and synthetic biology techniques are promising for the improvement of the gas fermentation process, and the first steps using advanced genetic tools have only recently been taken. Most gas fermentation organisms are not well-characterized, especially when compared to *C. acetobutylicum*, the model organism used in ABE fermentation. The first genome sequence to be published for a gas fermentation organism was in 2008, and subsequent advances made in the areas of metabolic engineering and synthetic biology will accelerate further. Syngas fermentation is always associated with acetic acid production, which lowers the culture pH. Redirecting the metabolic pathway towards solvent production by blocking acetic acid production might enhance ethanol production[10].

Scale-up status and commercialization

Commercial interest in gas fermentation has increased significantly over the past few years. Despite the increase in commercial interest, biomass gasification followed by syngas fermentation has yet to be achieved on a commercial scale. One of the principal technical challenges associated with commercialization is the successful scale-up of this process combination from pilot-scale to a commercial level. Among the many start-ups and commercial ventures that had taken up commercializing this technology, three companies feature prominently – INEOS Bio, Coskata and LanzaTech.

The first reports of commercialization came in with the establishment of Bioengineering Resources Inc. (BRI) with a transfer of syngas technology from bench-scale to industry. BRI functioned as a pilot unit from the year 2003 and INEOS Bio acquired this technology in 2008. INEOS Bio reported production rate of 100 gallons of ethanol per dry tonne of feedstock using patented isolates of *C. ljungdahlii* as biocatalyst. In commissioning with plans to begin operation in the third quarter of 2012, this plant is designed to produce ethanol from yard, vegetative and household waste and is also projected to produce 6 MW (gross) of electricity from unused syngas. This plant has a total planned capacity of 300 dry tonnes per day, producing 8 million gallons of ethanol per year[44]. LanzaTech announced completion of the first phase of a multi-phase partnership with Baosteel, China's largest steel producer: a 100,000 gal/year demonstration facility that converts waste carbon monoxide gas from the production facility at Baosteel into ethanol via gas fermentation technology of LanzaTech. The successful completion serves as a precursor to a commercial facility targeted for 2014. Coskata Inc. was also a bioenergy start-up and claimed to have biological catalysts that have been successful in commercial syngas fermentation process. The Coskata website (2012) reports a fully integrated demonstration-scale facility for syngas fermentation located in Madison, Pennsylvania, USA, that has accumulated more than 15,000 operating hours of producing ethanol from natural gas, wood chips and simulated waste materials.

Conclusion

Biofuel production from biomass-generated syngas has a potential to provide viable solutions for fulfiling future energy needs. It can be a good alternative to augment the present strategies researched and implemented by almost all the major economies to sustain their growth. Although it is an attractive and emerging technology, there are currently few major drawbacks for successful application in the commercial scale. Mass transfer limitation, syngas quality, microbial catalyst and product recovery are the major issues preventing the successful commercialization of syngas fermentation technology. To overcome these issues reactor designs, use of hollow fibre membrane and nanoparticles can be investigated. Researchers are also looking for potential thermophilic microorganisms utilizing CO or syngas as a sole carbon source.

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