Chapter 13
Progresses in Bioenergy Generation from CO_2: Mitigating the Climate Change

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13.1 Introduction

These days, the interest in the clean energy generation has been quickly expanded as a direct result of the monetary development around the world. To fulfill this developing need, a bounteous measure of non-renewable energy sources is required (Giri et al. 2020; Leung et al. 2014). The depletion of non-renewable energy sources is frequently considered as one of the dangers to nature in context of the carbon dioxide (CO_2) discharge. CO_2 is primary green house gas (GHG), present on the land surface, sea, and environment where animals, plants, and microorganisms, assimilates and produces it every day (Kapoor et al. 2020; Spigarelli and Kawatra 2013). Notwithstanding, the pattern of discharging and expending CO_2 must be adjusted essentially. To diminish the GHGs, CO_2 sequestration and conversion capacity has increased to a great extent. In any case, we must develop the techniques and measures for capturing the CO_2 as a feedstock. In this way, using CO_2 and converting it into synthetic substances, will be useful to mitigate the CO_2 emission (Peters et al. 2009). During the recent years, the transformation of CO_2 into value-added synthetic compounds utilizing various methods are getting an incredible consideration from the researchers as it results in reducing the harmful GHGs (Kumar et al. 2019; Sharma

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et al. 2020a, b). So, we need to find alternatives that uses the CO_2 present in the atmosphere and converts it into valuable products (Sharma and Kumar 2021). Methanol is one of the important product that can be made from CO_2. Methanol does not emit extra CO_2 into the atmosphere, and it has high volumetric and gravimetric energy density and is a very important fuel that is replacing the use of fossil fuels (Patterson et al. 2019). Its prime benefit is to reduce greenhouse gas emissions from vehicles. It has the highest hydrogen to carbon ratio in comparison with any liquid fuel and can be readily degraded in both aerobic and anaerobic environments. Methanol has the potential to reduce carbon emissions by 65–95%. It is highly versatile in making everyday products, and it is efficiently combustible, easily distributed, and widely available, making it affordable to use. Out of the total energy consumption of the world, 49% of it is met by fuels like gasoline, diesel, jetoils, etc. (Lewis and Nocera 2006). As compared to conventional fuels, its benefits are high as compared to gasoline and diesel. Recently, indeed, the various industries across the globe are using methanol as a crude material for making various items. Methanol is utilized in the production of solvents such as the acids. It can also be utilized in direct methanol powered devices which are utilized for the transformation reactions in the industries (Fig. 13.1). Methanol is viewed as the significant natural feedstocks that are utilized in businesses with a yearly production of 65 million tons around the world (Dalena et al. 2018). Various aspects of conversion of carbon dioxide to bioenergy based

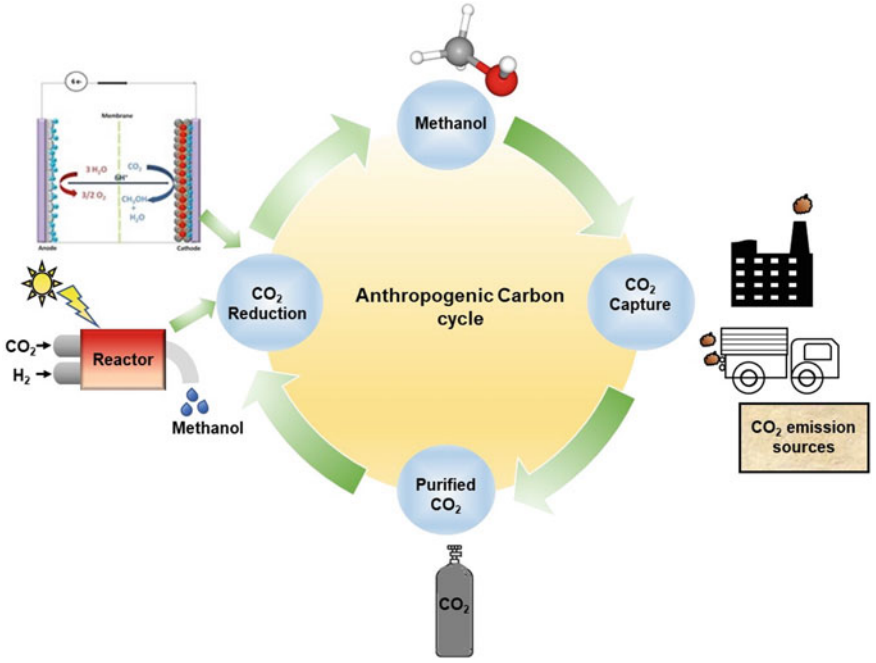

Fig. 13.1 Description of the anthropogenic carbon cycle for the production of methanol

products such as methanol and fixation of CO_2 using microbes and other biological entities have been discussed in this chapter.

13.2 Conversion of CO_2 into Methanol by Chemical Methods

The methanol production from direct hydrogenation of CO_2 is an attractive strategy, as this process has several advantages such as it requires less energy for product purification and fewer by-products formation. CO_2 can be valorized through hydrogenation, focusing on reverse water–gas shift reaction (RWGS), methanation, and methanol production (Gutterød et al. 2020). In literature, various metal organic frameworks have been reported for the CO_2 capture, and they have great potential to convert the atmospheric CO_2 in heterogeneous catalytic system. The methanol synthesis from CO_2 hydrogenation and RWGS is a thermodynamically limited reaction, and equilibrium conversion of CO_2 decreases with increasing reaction temperature; therefore, it needs a catalytic system (Kaisar and Sreedevi 2018). Methanol is also prepared by the hydrogenation of carbon dioxide by reverse water–gas shift reaction. The catalyst used is $Ni/Al_{12}O_{19,}$ and this process is largely used in an industrial scale (Samimi and Rahimpour 2019). Lately, it has been observed that indium oxide is a highly selective catalyst in the thermal hydrogenation of CO_2 to methanol, and hydrogenation of CO_2 to methanol is being carried out commercially using heterogeneous CuZnO supported on Al_2O_3 (Chun 2020). Methanol formed by carbon dioxide via catalytic CO_2 hydrogenation is efficient for storing energy and CO_2 capture. Methanol thus formed has a neutral carbon footprint and is a clean source of energy.

In the European Union, a pilot plant was built by the MefCO_2 project that produces 500 tons of methanol per year (Bowker 2019). In Iceland, CRI has a commercial plant that has 4000 metric tons per year of methanol production capacity. They utilize this renewable methanol for bio-diesel production, automobiles, and the production of synthetic material (Olah 2013). Nonetheless, the heterogeneous catalyst has numerous focal points regarding partition, strength, taking care of, cost, and reusing of the catalyst.

13.2.1 Heterogeneous Catalytic Method

Heterogeneous catalysts for conversion of CO_2 to methanol are widely used for the industrial purposes. It generally involves the rapid separation of fluid from the solid catalyst, and the catalyst that is used can be again produced (Table 13.1). Among heterogeneous catalysts, $Cu/ZnO/ZrO_2$ have been mostly studied due to their high selectivity and conversion rate. In this catalyst, ZnO increases the Cu dispersion and

Table 13.1 Various methods for conversion of CO_2 into methanol

S. No.	Methods	Catalysts/Photocatalysts/Electrode	Comments	References
1	Heterogenous	Cu ZnO ZrO_2	High selectivity and conversion rate	Zhong et al. (2020)
2	Homogenous	$Ru_3(CO)_{12}$ $MO(CO)_6$ $Rh(CO)_{12}$ $CO_2(CO)_8$	Involves rapid separation of methanol and recycling of catalyst.	Kothandaraman et al. (2016)
3	Electrochemical	Cu Fe Mo Pt Hg	Cu is considered as a more promising electrode, utilized in conversion of CO_2 into methanol and other value-added products	Albo et al. (2015)
4	Photochemical	CdS/TiO_2 Bi_2S_3/TiO_2	Reduction of CO_2 into methanol using visible light	Gondal et al. (2013)

both ZnO and ZrO_2 improve the stability and CO_2 absorption capacity. The incorporation of metal oxides such as Ga_2O_3, Al_2O_3, MgO, SiO_2, and La_2O_3 enhances the activity and modifies the redox properties (Zhong et al. 2020). Various companies such as Sinetix, HaldorTopsoe, and Mitsubishi Gas Chemical are producing a highly stable catalyst for the production of methanol (Al-Saydeh and Zaidi 2018).

13.2.2 Homogenous Catalytic Method

Different types of homogeneous catalysts are also being used for the conversion of CO_2 into valuable compounds (Table 13.1). The catalysts for CO_2 conversion are available in the form of metal complexes, organic solvents, and ionic solvents (Zarandi et al. 2019). Referring to different studies, it has been observed that some basic heterocyclic organic compounds like pyrimidine elevate the CO_2 reduction

reaction and its conversion as compared to other heterogeneous catalysts. Recently, it is observed that basic heterocyclic organic compounds like pyrimidine increase the reduction reaction of CO_2 conversion as compared to other homogeneous catalysts (Albo et al. 2015). A distinctive heterogeneous catalyst was tried for immediate CO_2 conversion into methanol. In a previous study, $Ru_3(CO)_{12}$ catalyst in the presence of potassium iodide was studied for the hydrogenation of CO_2 to CH_3, CH_4, and methanol (Tominaga et al. 1993). Furthermore, it was reported that $Ru_3(CO)_{12}KI$ was better for CO_2 conversion than another metal carbonyl including $Fe_2(CO)_9$, $Mo(Co)_6$, $Rh_4(CO)_{12}$, $W(CO)_6$ and $Co_2(CO)_8$ (Huff and Sanford 2011; Tominaga et al. 1993). Kothandaraman et al. (2016) firstly captured CO_2 directly from the air and converted it into methanol. In this process, Ru-based catalyst and polyamine were used for methanol production. After CO_2 conversion, methanol was separated and the catalyst was recycled to produce more methanol.

13.2.3 Electrochemical Reduction of CO_2 to Methanol

The electrochemical reduction method attracted the interest of the researcher which is eco-friendly and has economic benefits. This process is simple and can be used under ambient conditions (Zarandi et al. 2019). The electrochemical strategy is utilized for CO_2 conversion to important synthetic compounds, for example, methanol by utilizing electricity as the energy source. In this method, electric energy is applied to create a potential between two electrodes to transform CO_2 into reduced form (Yaashikaa et al. 2019). Reduced chemical species are obtained after the electrocatalytic CO_2 reduction reaction (Fig. 13.2). The electrolytes used in these reactions affect the reduction of CO_2. Solvents used also play a key role in maintaining pH, conductivity, and toxicity. Various experiments have been reported for CO_2 conversion on the terminals of metal (Kuhl et al. 2014). Various metal electrodes such as copper, ruthenium, molybdenum, titanium, iron, mercury, and platinum have been studied for electrochemical reduction of CO_2, but among them, copper (Cu) is one of the most promising electrodes (Albo et al. 2015).

The hydrogen evolution reaction (HER) is significant in the CO_2 electrocatalyst reduction in which water presents as an electrolyte. Consequently, the reported metals that have been utilized as electrocatalyst in CO_2 reduction should have moderately greater HER (Goeppert et al. 2014). In a previous study, it was found that methanol production rate was 1.2×10^{-4} $molm^{-2}$ s^{-1} on electrodeposited cuprous thin-film electrodes in potassium carbonate solution (Le et al. 2011). Moreover, MoS_2-rods/TiO_2 nanotubes electrodes were reported for electrochemical CO_2 reduction and found that CH_3OH yield reached 202.2 mgL^{-1} at 6 h (Li et al. 2014). Qu et al. (2005) reported the RuO_2/TiO_2 nanotubes and nanoparticles for the methanol production and showed 60.5% CO_2 conversion efficiency. Wu et al. (2019) revealed that when a cobalt phthalocyanine was dispersed on carbon nanotubes, it has high selectivity and catalytic activity for the electrochemical CO_2 reduction to methanol. Modification is done in electrocatalysts to increase the reduction efficiency and increase

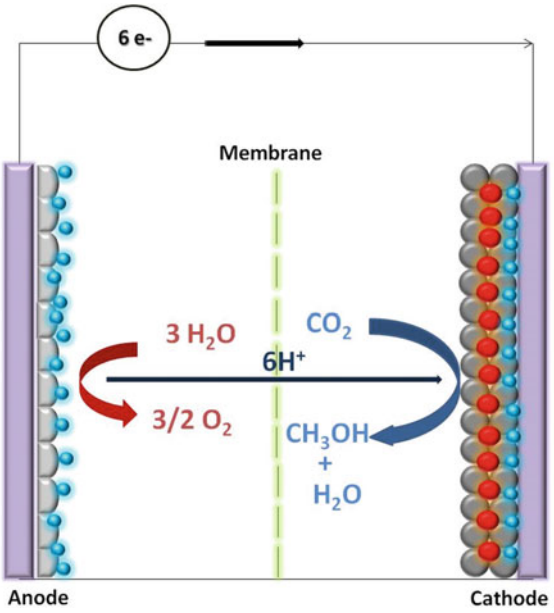

Fig. 13.2 Schematic representation of electrochemical system for the conversion of CO_2 into methanol

the faradaic efficiency. Recently, the catalysts are being modified and designed to control the dimensions of nanoparticles showing a mono-dispersive configuration (Zarandi et al. 2019). In most recent years, electrochemical CO_2 transformation is broadly utilized in a research field; however, it has not been effectively utilized in mechanical procedures.

13.2.4 Photochemical Reduction of CO_2 to Methanol

Normally, this CO_2 transformation technique is utilized to convert captured CO_2 to methanol and other value-added products by utilizing sunlight, (Fan et al. 2013) (Table 13.1). Nowadays, this technique has attracted the interest of people and is being considered as one of the most appealing strategies for the utilization of CO_2. The photocatalytic CO_2 transformation process is a blend of photochemical and photophysical procedures together (Gondal et al. 2013). Although this strategy has a few resemblances with electrolytic CO_2 reduction in both these methods, molecular catalyst is used. Various experiments have shown the ability of metal oxides and semiconductors such as titanium dioxide, silicon carbide, zinc oxide, and tungsten trioxide, for the conversion of CO_2 to methanol (Zhang et al. 2019). Li et al. (2012) proved that CdS/TiO_2 and Bi_2S_3/TiO_2 are promising photocatalysts to reduce CO_2 into methanol using visible light. The methanol production efficiency of TNTs-Bi_2S_3 and TNTs-Bi_2S_3 was 224.6 μmol/L and 159.5 μmol/L, respectively. In another study, the ability of Nd/TiO_2 synthesized by the sol–gel method was studied, and they found

that the maximum methanol production yield was 184.8 μmol/g for 8 h (Luo et al. 2009). The main drawback of CO_2 reduction to methanol using the photochemical method is that the reaction is reversible. Thus, to alleviate the methanol oxidation, it is important to find new methods so it can be applied to the industrial level too.

13.2.5 MOF for CO_2 Reduction

Various classes of a porous material including zeolites, porous organic polymers, porous carbons, covalent organic frameworks (COFs), and metal–organic frameworks (MOFs) have been reported for CO_2 capture (Ding et al. 2019). Recently, MOFs are emerging out as a new class of crystalline materials due to their unique features such as large surface area, crystalline nature, handy pore structure, and chemical tunability (Fig. 13.3) (Maina et al. 2017). Debatin et al. (2010) synthesized zinc-imidazolate-4-amide-5-imidate framework, and CO_2 uptake capacity of these MOF was found to be 2.1 mmol g^{1}at 1 bar and 298 K. Furthermore, MOFs incorporated with nanoparticles, metal oxides, and other catalytically active species have also been studied for CO_2 conversion. As an example, Ag NPs were impregnated into the cavities of MIL-101 by a liquid impregnation–reduction method. The resultant Ag@MIL-101 materials had excellent catalytic activity (96.5%) and stability

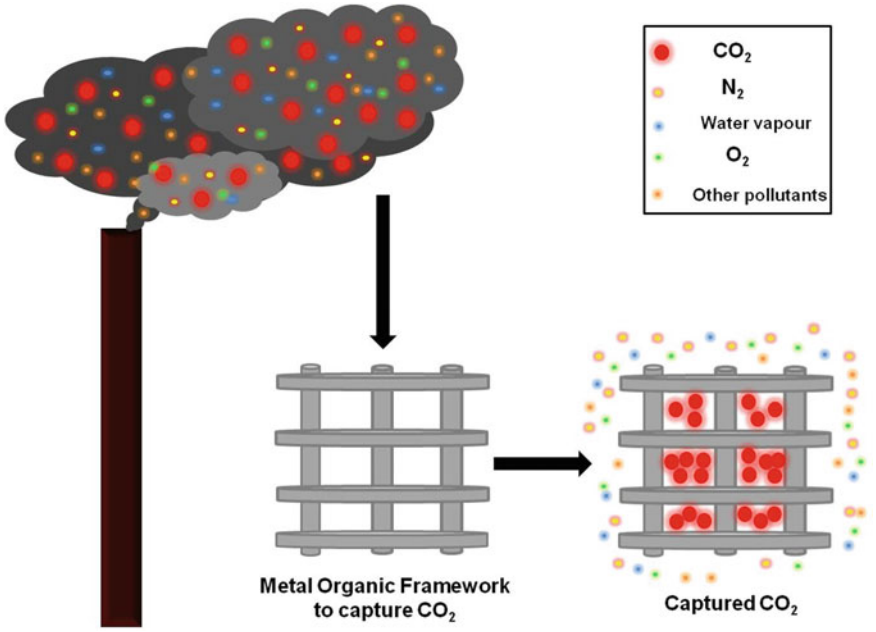

Fig. 13.3 Metal organic framework (MOF) for the CO_2 capture and conversion

at 50 °C (Liu et al. 2015 Sharma et al. 2018). Gutterød et al. (2020) studied the role of the platinum nanoparticles impregnated in ZR-based UiO-67 MOF in the hydrogenation of CO_2 into methanol using a kinetic analysis. In the resultant MOF, methanol was formed at the interface of platinum nanoparticles and linker-deficient Zr_6O_8 nodes.

13.3 Use of Biological Systems for CO_2 Capture and Utilization

Various photosynthetic microbes such as algae and bacteria can assimilate CO_2 (Table 13.2). Moreover, some of the autotrophic bacteria were also studied for utilizing CO_2. The most important advantage of microbial CO_2 conversion is the natural ability of microbes to take up CO_2 through their metabolic pathways. The CO_2 fixing routes have been developed through enzymatic processing of CO_2 by formulating C–H, C–O, and C–C bonds cleavage (Ramsey et al. 2009). The most commonly used pathways for CO_2 reduction are pentose phosphate, citric acid cycle (Peters et al. 2011). Furthermore, various microbial enzymes have been utilized for the conversion of CO_2. The direct use of microbes is affected by environmental factors, low product yield, and growth. In this context, protein engineering and synthetic biology are ideal methods for engineering the microbes, and thus making the process economically viable.

Table 13.2 Biological agents involved in conversion of CO_2

Class	Species	Comments	References
Algae	*Nannachlorissp* *Chlorella vulgaris* *Chlamydomonas reinhardtti* *Scendesmusquadricauda*	High photosynthesis rate Rapid reproduction rate	Pavlik et al. (2017); Sharma et al. (2020a, b)
Bacteria	*Clostridumaceticum* *Clostridium kluyveri* *Clostridium ljungdahli* *Acetobacteriumkloodii*	*Clostridium*is considered best for CO_2 fixation and having numerous biotechnological applications Assorted pathway for creation of metabolites Resistance to poisonous metabolites and substrates	Jajesniak et al. 2014
Yeast	*Saccharomyces cerevisiae*	Involved in CO_2 fixation	Zelle et al. 2008

13.3.1 Algae for CO_2 Fixation

Algae are present throughout the world and one of the most commonly researched organisms for CO_2 fixation. Algae can be found in freshwater–water or marine ecosystems individually or in a form of chains. They lack stems, leaves, or roots and have a vast range of sizes. CO_2 is utilized as a carbon source by them for photoautotrophic growth and produces over half of the atmospheric oxygen (Shi and Theg 2013). As algae use the CO_2 by the Calvin–Benson pathway and convert the inorganic carbon to organic compounds. One molecule of phosphoglycerate is diverted to focal on pathways of metabolic activity, while the other is used in the continuation of the cycle. The key enzyme for carboxylation of CO_2 is RuBisCO, and it has a high affinity for CO_2 and O_2. So, it creates a problem in an environment because of the high O_2 affinity and low fixations present in the atmosphere. Algae possess three significant constituents of CCM including dynamic bicarbonate take-up transporters, a set of carbonic anhydrases (CAs), and a subcellular small-scale compartment inside which most of RuBisCO is found. Furthermore, micro and macroalgae can fix inorganic carbon effectively. Various algal species, such as *Nannochlorissp., Scenedesmus quadricauda, Chlorella vulgaris*, *Nannochloropsis sp.*, and *Chlamydomonas reinhardtii*, have been studied to CO_2 fixation (Pavlik et al. 2017). Microalgae have a high photosynthesis rate due to their small size, rapid reproduction rate, and synthesis of oil, pigment, etc., because of its complex metabolic reactions. Hence, making microalgae is highly efficient for converting carbon dioxide (Yen et al. 2013). *Chlamydomonas reinhardtii* and *Volvox carteri* have been genetically engineered for increasing the CO_2 fixation efficiency (Beer et al. 2009; Walker et al. 2005). To improve the CO_2 fixation efficiency of algae species, screening and domestication would be major promising strategies.

13.3.2 Bacteria for CO_2 Fixation

Various carbon-capturing bacteria are *Acetobacterium woodii, Clostridium aceticum, Clostridium kluyveri, Clostridium ljungdahlii, Rhodopseudomonas palustris, Rhodococcus erythropolis, Ralstonia eutropha, Synecococcus elongatus, Rhodobacter sphaeroides,* etc. (Jajesniak et al. 2014). Among various bacteria reported for CO_2 fixation, *Clostridium* fixes CO_2 using the Wood–Ljungdahl pathway. They are anaerobic and gram-positive microbes, but their cultivation is difficult and expensive because of its obligate nature (Tracy et al. 2012). Numerous strains in the *Clostridium* class can fix CO_2, as a carbon source. *Clostridia* shows numerous attractive attributes for biotechnological applications such as the capacity to use a wide range of carbon substrates, assorted pathways for the creation of helpful metabolites, and resistance to poisonous metabolites and substrates (Durre and Eikmanns 2015). Typical environmental condition is normally deadly to most of its species.

Early work with *Clostridium* concentrated mostly on the creation of acidic corrosive and related items. In any case, the collection of hereditary material relevant to *Clostridia* has altogether extended after the improvement of plasmid DNA innovations and chromosomal control advances. The utilization of the portable gathering II introns for focused quality disturbance (Targetron or ClosTron) is well known for the hereditary building of *Clostridium*. The utilization of ClosTron was shown by designing *Clostridium acetobutylicum* for butanol–ethanol formation (Cooksley et al. 2012). Moreover, in the cyanobacterium *Synochococcus elongates the* carbon assimilation mechanism was studied, and it produces 2,3-butanediol from CO_2 and glucose in dark (Kanno et al. 2017). Furthermore, the various microbial enzymes has been used for the conversion of CO_2. Formate dehydrogenase enzyme is a good biological catalyst known for its reversible reduction of CO_2 (Ruiz-Valencia et al. 2020). Another enzyme used for the conversion of CO_2 is carbonic anhydrase. It is present in various organisms like eubacteria, vertebrates, algae, archaea, plants, and animals (Moroney and Ynalvez 2007; Sharma and Kumar 2020). This enzyme is efficient in capturing CO_2 in a cost-effective and eco-friendly manner as raw materials such as metal oxide ores, industrial waste, and marble mines are easily available (Bhagat et al. 2018). In recent study, carbonic anhydrase immobilized onto electrospun nanofiber is used for the conversion of CO_2 into bicarbonates, and the bicarbonate solution formed was utilized for microalgae growth (Jun et al. 2020). Moreover, an organic procedure for CH_4 formation from CO_2 is named as biogenic methane. Nitrogenase is an ATP-dependent enzyme that carries out the multi-electron reduction of an inert molecule. Fixen et al. (2016) expressed nitrogenase enzyme in an anoxygenic phototroph of *Rhodopseudomonas palustris* and found that it is capable of CO_2 reduction to methane in the presence of light under in vivo condition.

In another study, Zhang et al. (2013) expressed phosphoribulokinase (PRK) with ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) in *E. coli* and converted CO_2 into a fermentation product. Microbes can be used as biocatalysts for converting CO_2 into useful products. They can be used in microbial electrochemical technologies using these biocatalysts in electrochemical cells to supply or gain electrons from various biochemical reactions that utilize CO_2 as a carbon source for the production of fuels and other products. Worldwide attempts are being made to convert methane into methanol using CO_2 as a source; due to the increase in production of methanol, its price is also decreasing and has got equal to the price of glucose (Antoniewicz 2019).

13.3.3 Yeast for CO_2 Fixation

As compared to *E. coli*, *Saccharomyces cerevisiae* has pulled in less consideration as a potential answer for anthropogenic CO_2 emanation (Guadalupe-Medina et al. 2013). To acquire a critical number of useful RuBisCO units, co-articulation of *E. coli* protein collapsing chaperones GroEL and GroES was essential. The created framework was described by a 90% decrease in the side effect glycerol development

and a 10% expansion in ethanol production, for a sugar-constrained culture (Natesh et al. 2018). Another pertinent model is the improved creation of malic corrosive in *S. cerevisiae* by building a CO_2 focusing pathway that returns through the carboxylation of pyruvate (Zelle et al. 2008).

13.4 Bio-based Products from CO_2

13.4.1 Bioplastics

Many bacteria are capable of converting CO_2 into eco-friendly plastic, i.e, polyhydroxybutyrate (PHB) using sunlight. PHB is a biodegradable as well as biocompatible, thermoplastic as comparable to petrochemically inferred polypropylene (Markl et al. 2018). *Cupriavidusnecator* is a gram-negative facultative hydrogen oxidizing bacterium; it produces single cell proteins and polyhydroxybutyrate (PHB) depending on the supply of nutrients. It can be converted into valuable products like crotonic acid and other fuels (Yu 2018). This bacterium was cultured on a mixture of gases like hydrogen, oxygen, and carbon dioxide. *C. necator* fixes CO_2 under aerobic conditions using the Calvin–Benson–Bassham cycle and has more CO_2 fixing capacity as compared to green algae. It grows on glucose and glycerol under aerobic conditions (Shimizu et al. 2015). There are certain pathways for converting inorganic CO_2 into its organic form. This has instigated an impressive enthusiasm for the business creation of this polymer. PHB is appropriate for use as nourishment bundling material taking into account its protection from water and UV radiation and its impermeability to O_2. Additionally, it is being applied in careful stitches. Significantly, PHB can be prepared to utilize previous advances and in blend with other manufactured polymers (Mozumder et al. 2015).

13.4.2 Bio-alcohol

The use of CO_2 to synthesize bio-alcohols have concentrated on ethanol using microbial genera such as *Rhodobacter spp.* The utilization of ethanol as a substitution for ordinary gas is tested by the fact that ethanol has short half life, low vitality, and is destructive to current motor and fuel foundation (Costa et al. 2015). Further, it promptly assimilates the water and weakening in the capacity tank. The natural synthesis of isopropanol is possible using microbial systems. Similarly, it can be used to esterify fat and oil for bio-diesel production, which diminishes its propensity to take the shape at decreasing temperatures.

13.4.3 Bio-diesel

Because of their high lipid contents and simplicity of development, the bio-diesel is used as non-inexhaustible oil-based fuel. Lipids, as triacylglycerides (TAGs), commonly provide the energy to the living cells. Once removed, the lipid can be changed into unsaturated fatty acid methyl esters (FAME) or bio-diesel through transesterification (Sharma et al. 2012; Sharma et al. 2019). The physical attributes of FAME are like those of fossil fuels. Critically, it is non-poisonous and also biodegradable. The utilization of bio-diesel as a low-mix part in the vehicle fuel does not require any progressions in the framework.

13.5 Conclusion

Carbon dioxide transformation is introducing both a chance and a test widely for the supportability of conditions. The fundamental systems of CO_2 mitigation should concentrate on the use of CO_2, reusing CO_2 with the sustainable methods. In this way, the change of CO_2 into synthetic products for example, methanol will expend an enormous conversion of captured CO_2 where the market size of methanol is possibly broad. Moreover, the synthesized methanol can be utilized rather than the non-renewable energy source, accordingly lessening the reliance on petroleum based derivative and contributing to the market development of CO_2 use. Thus, the various strategies for CO_2 transformation into methanol have been accounted in this chapter. This incorporates homogeneous/heterogeneous catalysts, electrochemical, and photochemical based methods. In any case, the superior in the CO_2 transformation procedure can be accomplished by utilizing a successful impetus. The poor item selectivity and the low/high response temperatures are viewed as the primary boundaries in the heterogeneous CO_2 conversion process. The above findings showed that among different strategies proposed for CO_2 transformation to methanol or to other value added products, the electrochemical cells are ideal over various other techniques. Also, photochemical procedures offer an appealing way to convert CO_2 to methanol utilizing sun-based energy. In future, more techniques should be discovered which use the principles of green chemistry and convert more CO_2 into methanol rather than emitting other hazardous by-products. The techniques should be cost effective and should be implanted on large scale in an environment friendly manner.

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References

Albo J, Alvarez-Guerra M, Castaño P, Irabien A (2015) Towards the electrochemical conversion of carbon dioxide into methanol. Green Chem 17(4):2304–2324

Al-Saydeh SA, Zaidi SJ (2018) Carbon dioxide conversion to methanol: opportunities and fundamental challenges. Carbon Dioxide Chemistry, Capture and Oil Recovery, Iyad Karamé, Janah Shaya and Hassan Srour, IntechOpen. https://doi.org/10.5772/intechopen.74779

Antoniewicz MR (2019) Synthetic methylotrophy: Strategies to assimilate methanol for growth and chemicals production. CurrOpin Biotech 59:165–174

Beer LL, Boyd ES, Peters JW, Posewitz MC (2009) Engineering algae for biohydrogenandbiofuel production. Curr Opin Biotechnol 20:264–271

Bhagat C, Dudhagara P, Tank S (2018) Trends, application and future prospectives of microbial carbonic anhydrase mediated carbonation process for CCUS. J Appl Microbiol 24(2):316–335

Bowker M (2019) Methanol synthesis from CO_2 hydrogenation. Chem Cat Chem 11(17):1867–3880

Costa RL, Oliveira TV, de Ferreira JS, Cardoso VL, Batista FR (2015) Prospective technology on bioethanol production from photofermentation. BioresourTechnol 181:330–337

Cooksley CM, Zhang Y, Wang H, Redl S, Winzer K, Minton NP (2012) Targeted mutagenesis of the *Clostridium acetobutylicum* acetone-butanol-ethanol fermentation pathway. Metab Eng 14(6):630–641

Chun YN, HG Song (2020) Microwave-induced carbon-CO_2 gasification for energy conversion. Energy 190:116386

Dalena F, Senatore A, Basile M, Knani S, Basile A, Iulianelli A (2018) Advances in methanol production and utilization, with particular emphasis toward hydrogen generation via membrane reactor technology. Membranes 8(4):1–27

Debatin F, Thomas A, Kelling A, Hedin N, Bacsik Z, Senkovska I, Kaskel S, Junginger M, Müller H, Schilde U, Jäger C, Friedrich A, Holdt HJ (2010) In situ synthesis of an imidazolate-4-amide-5-imidate ligand and formation of a microporous zinc-organic framework with H_2- and CO_2-storage ability. Angew Chem Int Ed Engl 49(7):1258–1262

Ding M, Flaig RW, Jiang HL, Yaghi OM (2019) Carbon capture and conversion using metal–organic frameworks and MOF-based materials. Chem Soc Rev 48(10):2783–2828

Durre P, Eikmanns JB (2015) C1-carbon sources for chemical and fuel production by microbial gas fermentation. Curr Opin Biotech 35:63–72

Fan W, Zhang Q, Wang Y (2013) Semiconductor-based nanocomposites for photocatalytic H2production and CO2 conversion. Phys Chem Chem Phys 15(8):2632–2649

Fixen KR, Zheng Y, Harris DF, Shaw S, Yang ZY, Dean DR, Harwood CS (2016) Light-driven carbon dioxide reduction to methane by nitrogenase in a photosynthetic bacterium. Proc Natl Acad Sci 113(36):10163–10167

Giri A, Sharma V, Thakur S, Sharma T, Kumar A, Pant D (2020) Engineering of microbial carbonic anhydrase for enhanced carbon sequestration. In: Kumar A, Sharma S (eds) Chemo-biological systems for CO_2 utilization. Taylor and Francis Group

Goeppert A, Czaun M, Jones JP, Prakash GKS, Olah GA (2014) Recycling of carbon dioxide to methanol and derived products–closing the loo. Chem Soc Rev 43(23):7995–8048

Gondal MA, Ali MA, Dastageer MA, Chang X (2013) CO_2 conversion into methanol using granular silicon carbide (α6H-SiC): a comparative evaluation of 355 nm laser and xenon mercury broad band radiation sources. Catal Lett 143(1):108–117

Guadalupe-Medina V, Wisselink HW, Lutti MA, HulsterE DaranJMPronk JT, Mris A (2013) Carbon dioxide fixation by Calvin cycle enzymes improves ethanol yield in yeast. Biotechnol Biofuel 125:1–12

Gutterød ES, Lazzarini A, Fjermestad T, Kaur G, Manzoli M, Bordiga S, Svelle S, Lillerud KP, Skúlason E, Øien-Ødegaard S, Nova A, Olsbye U (2020) Hydrogenation of CO_2 to methanol by Pt nanoparticles Encapsulated in UiO-67: deciphering the role of the metal-organic framework. J Am Chem Soc 142(2):999–1009

Huff CA, Sanford MS (2011) Cascade catalysis for the homogeneous hydrogenation of CO_2 to methanol. J Am Chem Soc 133(45):18122–18125

Jajesniak P, Ali H, Wong TS (2014) Carbon dioxide capture and utilization using biological systems: opportunities and challenges. J Bioprocess Biotech 4(3):1–15

Jun SH, Yang J, Jeon H, Kim HS, Pack SP, Jin ES, Kim J (2020) Stabilized and immobilized carbonic anhydrase on electrospun nanofibers for enzymatic CO_2 conversion and utilization in expedited microalgal growth. Environ Sci Technol 54(2):1223–1231

Kaisar A, Sreedevi U (2018) Greenhouse gas CO_2 hydrogenation to fuels: a thermodynamic analysis. Environ Prog Sustain Energy 38:98–111

Kanno M, Carroll AL, Atsumi S (2017) Global metabolic rewiring for improved CO_2 fixation and chemical production in cyanobacteria. Nat Commun 8:1–11

Kothandaraman J, Goeppert A, Czaun M, Olah GA, Prakash GK (2016) Conversion of CO_2 from air into methanol using a polyamine and a homogeneous ruthenium catalyst. J Am Chem Soc 138(3):778–781

Kapoor R, Ghosh P, Tyagi B, Kumar V, Vijay V, ThakurIS Kamyab H, Nguyen DD, Kumar A (2020) Advances in biogas valorization and utilization systems: a comprehensive review. J Clean Prod 273:123052

Kuhl KP, Hatsukade T, Cave ER, Abram DN, Kibsgaard J, Jaramillo TF (2014) Electrocatalytic conversion of carbon dioxide to methane and methanol on transition metal surfaces. J Am Chem Soc 136(40):14107–1411

Kumar A, Sharma T, Mulla SI, Kamyab H, Pant D, Sharma S (2019) Let's protect our earth: environmental challenges and implications. In: Kumar A, Sharma S (eds) Microbes and enzymes in soil health and bioremediation. Springer Singapore, Singapore, pp 1–10

Le M, Ren Z, Zhang Z, Sprunger PT, Kurtz RL, Flake JC (2011) Electrochemical reduction of CO_2 to CH_3OH at copper oxide surface. J Electrochem Soc 158(5):45–49

Leung DYC, Caramanna G, Maroto-Valer MM (2014) An overview of current status of carbon-dioxide capture and storage technologies. Renew Sustain Energy Rev 39:426–443

Lewis NS, Nocera DG (2006) Powering the planet: chemical challenges in solar energy utilization. Proc Natl Acad Sci 103:15729

Li P, Hu H, Xu J, Jing H, Peng H, Lu J, Lu F (2014) High-efficiency synergistic conversion of CO_2 to methanol using Fe_2O_3 nanotubes modified with double-layer Cu_2O spheres. Nanoscale 6:11380–11386

Li X, Liu H, Luo D, Li J, Huang Y, Li H, Fang Y, Xu Y, Li Z (2012) Adsorption of CO_2 on heterostructure CdS (Bi2S3)/TiO_2 nanotubephotocatalysts and their photocatalytic activities in the reduction of CO_2 to methanolunder visible light irradiation. Chem Eng 180:151–158

LiuXH Ma JG, Niu Z, YangGM ChengP (2015) An efficient nanoscale heterogeneous catalyst for the capture and conversion of carbon dioxide at ambient pressure. Angew Chem Int Ed 54:988–991

Luo D, Chen C, Zhang N, Hong S, Wu H, Liu Z (2009) Characterization and DFT research ofNd/TiO_2: photocatalyst for synthesis of methanol from CO_2 and H_2O. Z Physic Chem 223(12):1465–1476

MainaJW Pozo-Gonzalo C, Kong L, SchützJ HillM, Dumée F (2017) Metal organic framework based catalysts for CO_2 conversion. Mater Horiz 4(3):345–361

Markl E, Grunbichler H, Lackner M (2018) PHB-Bio based and biodegradable replacement for PP: a review. Nov Tech Nutr Food Sci 2

Moroney JV, Ynalvez RA (2007) Proposed carbon dioxide concentrating mechanism in *Chlamydomonas reinhardtii*. Eukaryot Cell 6(8):1251–1259

Mozumder SI, Garcia-Gonzalez L, Wever HD, Volcke EIP (2015) Poly(3-hydroxybutyrate) (PHB) production from CO_2: model development and process optimization. Biochem Eng J98:107–116

Natesh R, Clare DK, Farr GW, Horwich AL, Saibil HR (2018) A two-domain folding intermediate of RuBisCO in complex with the GroEL chaperonin. Int J Biol Macromol 118:671–675

Olah GA (2013) Towards Oil Independence through renewable methanol chemistry. Angew Chem Int Ed52:104–117

Patterson BD, Mo F, Borgschulte A, Hillestad M, Joos F, Kristiansen T, Sunde S, van Bokhoven JA (2019) Renewable CO_2 recycling and synthetic fuel production in a marine environment. Proc Natl Acad Sci 116(25):12212–12219

Pavlik D, ZhongY Daiek C, Liao W, Morgan R, Clary W, Liu Y (2017) Microalgae cultivation for carbon dioxide sequestration and protein production using a high-efficiency photobioreactor system. Algal Res 25:413–420

Peters M, Mueller T, Leitner W (2009) CO_2: from waste to value. Chem Eng 813:46–47

Peters M, Kohler B, Kuckshinrichs W, Leitner W, Markewitz P, Muller T (2011) Chemical technologies for exploiting and recycling carbon dioxide into the value chain. Chem Sus Chem 4:1216–1240

Qu J, Zhang X, Wang Y, Xie C (2005) Electrochemical reduction of CO_2 on RuO_2/TiO_2 nanotubes composite modified Pt electrode. Electrochim Acta 50(16):3576–3580

Ramsey E, Sun Q, Zhang Z, Zhang C, Gou W (2009) Mini-review: green sustainable processes using supercritical fluid carbon dioxide. J Environ Sci 21:720–726

Ruiz-Valencia A, Benmeziane D, Pen N, Petit E, Bonniol V, Belleville MP, Paolucci D, Sanchez-Marcano J, Soussan L (2020) CO_2 valorization by a new microbiological process, Catal Today 346:106–111

SamimiF HamediN, Rahimpour MR (2019) Green methanol production process from indirect CO_2 conversion: RWGS reactor versus RWGS membrane reactor. J Environ Chem Eng 7(1):102813

Sharma A, Shadiya Sharma T, Kumar R, Meena K, Kanwar SS (2019) Biodiesel and the potential role of microbial lipases in its production. In: Arora P (ed) Microbial technology for the welfare of society. Microorganisms for Sustainability, Springer, Singapore, pp 83–99

Sharma A, Sharma T, Meena KR, Kumar A, Kanwar SS (2018) High throughput synthesis of ethyl pyruvate by employing superparamagnetic iron nanoparticles-bound esterase. Process Biochem 71:109–117

Sharma KK, Schumann H, Schenk PM (2012) High lipid induction in microalgae for biodiesel production. Energies 5:1532–1553

Sharma T, Sharma A, Sharma S, Giri A, Pant D Kumar A (2020) Recent developmentsin CO_2 capture and conversion technologies. In: Kumar A, Sharma S (eds) Chemo-biological systems for CO_2 utilization. Taylor and Francis Group; pp 1–14

Sharma T, Kumar A (2020) Efficient reduction of CO_2 using a novel carbonic anhydrase producing *Corynebacterium flavescens* Environ Eng Res 26(3): 1:1–9

Sharma T, Sharma S, Kamyab H, Kumar A (2020) Energizing the CO_2 utilization by chemo-enzymatic approaches and potentiality of carbonic anhydrases: a review. J Clean Prod 247:1–12

Shimizu R, Dempo Y, Nakayama Y, Nakamura S, Bamba T, Fukusaki E, Fukui T (2015) New insight into the role of the calvin cycle: reutilization of CO_2 emitted through sugar degradation. Sci Rep 1:1–10

Shi LX, Theg SM (2013) The chloroplast protein import system: from algae to trees. Biochim Biophys Acta 1833:314–331

Spigarelli BP, Kawatra SK (2013) Opportunities and challenges in carbon dioxide capture. J CO_2 Utilization 1:69–87

Tominaga K, Sasaki Y, Kawai M, Watanabe T, Saito M (1993) Ruthenium complex catalysed-hydrogenation of carbon dioxide to carbon monoxide, methanol and methane. J Chem Soc 7:629–631

Tracy BP, Jones SW, Fas AG, Indurthi DC, Papoutsakis ET (2012) Clostridia: theimportance of their exceptional substrate and metabolite diversity for biofuels andbiorefinery applications. Curr Opin Biotechnol 23:364–381

Walker TL, Collet C, Purton S (2005) Algal transgenics in the genomic era. J Phycol 41 1077–1093

Yaashikaa PR, Kumar PS, Varjani SJ, Saravanan A (2019) A review on photochemical, biochemical and electrochemical transformation of CO_2 into value-added products. J CO_2 Utilization 33:131–147

YenHW HuIC, Chen CY, Ho SH, Lee DJ, Chang JS (2013) Microalgae-based biorefinery from biofuels to natural products. Biores Tech 135:166–174

Yu J (2018) Fixation of carbon dioxide by a hydrogen-oxidizing bacterium for value-added products. World J Microbiol Biotechnol 34:1–7

Zarandi RF, Rezaei B, Ghaziaskar HS, Ensafi AA (2019) Electrochemical reduction of CO_2 to ethanol using copper nanofoam electrode and 1-butyl-3-methyl-imidazolium bromide as the homogeneous co-catalyst. J Environ Chem Eng 7(3):1–7

Zelle RM, Hulster E, Winden WA, Waard P, Dijkema C, Winkler AA, Geertman JM, Dijken JP, Pronk JT, Maris JA (2008) Malic acid production by *Saccharomyces cerevisiae.* Appl Environ Microbiol 74:2766–2777

Zhang F, Wang X, LiuH LiuC, Wan Y, Long Y, C Z (2019) Recent advances and applications of semiconductor photocatalytic technology. App Sci 9:2489

Zhong J, Yang X, Wu Z, Liang B, Huang Y, Zhang T (2020) State of the art and perspectives in heterogeneous catalysis of CO_2 hydrogenation to methanol. Chem Soc Rev 49(5):1385–1413

Zhang X, Wu Z, Zhang X, Li L, Li Y, Xu H, Li X, Yu X, Zhang Z, Liang Y, Wang H (2017) Highly selective and active CO_2 reduction electrocatalysts based on cobalt phthalocyanine/carbon nanotube hybrid structures. Nat Commun 8:14675

Sharma T, Kumar A (2021) Bioprocess development for efficient conversion of CO_2 into calcium carbonate using keratin microparticles immobilized Corynebacterium flavescens. Process Biochem 100:171–177