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FACULTY OF CHEMISTRY

DEPARTMENT OF ORGANIC CHEMISTRY, BIOCHEMISTRY AND CATALYSIS

MSc Thesis - literature report

Catalytic amino acid production from biomass-derived intermediates

MASTER: CHEMISTRY OF ADVANCED MATERIALS

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CONTENT

1. Biomass – a vast source of biofuels and biochemicals

Due to the rapid population growth and vast economic developments nowadays there is an increase in global energy demand that is estimated to double between 2000 and 2035 [1]. Fossil fuel sources, such as crude oil, coal and natural gas currently hold the major share of energy supply. However, these sources are non-renewable and global petroleum production is predicted to peak by 2020 due to increasing demand for chemical industries, before decaying. The first oil crises from 1973 raised some questions regarding the availability of traditional oil and gas sources in the years that follow.

Another major concern of the 21st century is the increasing levels of greenhouse emissions (CO_2 in special) caused by the enormous consumption of fossil fuels. The global CO_2 emissions reached an all-time record of 41.5 ± 4.4 billion tones in 2017, contributing to an atmospheric CO_2 concentration of 408 ppm, the highest since the beginning of the industrial revolution. If this situation continues, global average temperatures are estimated to increase drastically in the range of 2.5 – 5.4 °C [1]. In the same manner, global warming is a major threat to humankind as well as to the biosphere if we think at the increased rate and intensity of many climate catastrophes from recent time. In order to control global warming, several countries have issued stringent regulations to reduce the utilization of fossil fuels, moving towards a carbon-neutral society. For example, a part of the European Union goal was to expand the renewable energy market share to 20% of the total energy supply by 2020. Due to this situation created worldwide the scientists from many countries try to find alternative pathways to replace the actual industry which is based almost in totally on petroleum with an industry based on clean, sustainable resources for the production of fuels and chemicals.

Various renewable resources are available for the production of energy and/or chemicals. Some of these resources are: wind, geothermal, solar, hydropower and of course, biomass. Although renewable energy from wind and water holds considerable potential, it is insufficient and incapable to fill the entire global energy demand. Whereas solar energy possibly provides a more final solution to the problem, it will only be able to do so in the longer run [2]. For a short and medium term solution to the deficit of both sustainable energy and renewable carbon, most experts look to biomass as a most viable alternative source. As a highly abundant natural carbon source, biomass is considered a promising renewable alternative to fossil fuels that can be transformed into a wide range of value-added chemicals, clean solvents and biodiesel. Global annual production of biomass is estimated to be greater than 10 billion tons (dry basis), equating to more than 10% of global energy supply. Untapped biomass sources could generate a huge amount of energy, equivalent to more than 2 billion tons of

standard coal. The National Renewable Energy Action Plans estimated that biomass would provide around 42% of the total renewable energy needed for electricity, heating and cooling by 2020. Several biomass resources such as animal waste, agricultural crops, wood and aquatic plants are available for the production of sustainable chemicals. If we think at the fuels, which are of great necessity in our society, we realize that the humankind is on the verge of collapse. Bearing this in mind, we need to give it a chance to the biofuels because this is the future. The first generation of biofuels, encompassing bioethanol and biodisel, has already appeared on the market and shown both its potential and limitations. As bioethanol at present can only be used in a mixture with traditional gasoline, its potential as a long-term renewable fossil fuel alternative is severely limited. The same is largely true for biodiesel, although certain adapted engines have been shown to be capable of running on pure biodiesel [2]. Moreover, concerns persist that a large production of the first generation biofuels might represent a threat for global food supply, already strained by an increasing population. These problems could be avoided or mitigated by replacing the first generation biofuels with products derived from lignocellulosic biomass.

Lignocellulosic biomass is the most abundant and bio-renewable resource, with great potential for sustainable production of chemicals and fuels [3]. Lignocellulose functions as the most important structural component in a majority of plants, making it widely available in much larger quantities than starch, oils and fats, the source materials of first generation biofuels [2]. Biochemically, living systems produce a large number of organic molecules such as carbohydrates, fats and oils, phospholipids and glycolipids, waxes, steroids, proteins and nucleotides. Among them, carbohydrates are the primary energy-storage molecules. Carbohydrates are the main structural components of the cell walls of plants, in which the carbohydrate polymers, namely cellulose and hemicellulose, are tightly bound to the lignin. Any materials rich in cellulose, hemicellulose and lignin are commonly referred to as lignocellulosic biomass. For example, wood, bamboo, grass and their derived pulp and paper, and agricultural residues like corn stover and sugarcane bagasse are typical sources of lignocellulosic biomass. The global amount of terrestrial plant biomass produced annually through photosynthesis has been estimated to be about 56.8×10^9 tonnes of elemental carbon. Lignocellulose is estimated to make up between 70 and 95% of this amount [2].

Figure 1 displays the weight percentage of cellulose, hemicellulose and lignin in some typical biological sources such as pinaster, eucalyptus globules, wheat straw, sorghum stalks, bamboo and banana pseudo-stems [3]. Generally, most of the lignocellulosic biomass contains 35-50% cellulose, 20-35% hemicellulose and 10-25% lignin. Unfortunately, these components are indigestible by

humans, but are readily available in several industrial waste streams, especially from the paper and agricultural industries. This severs to the direct competition between lignocellulose valorization and human food supply.

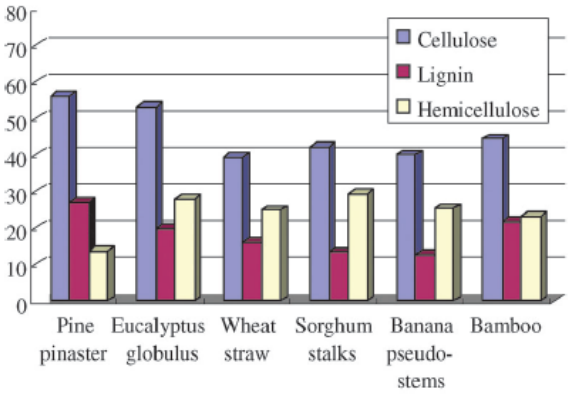


Figure 1. The weight percentage of cellulose, hemicelluloses and lignin in some typical biological resources: pine pinaster, eucalyptus globules, wheat straw, sorghum stalk, bamboo and banana pseudo-stems [3]

Since cellulose is the main component of lignocellulosic biomass it is imperative to know more about it. Cellulose is one of the most abundant compounds on earth because it is contained in almost all woody materials. It has the same molecular formula as amylose, one of the main components of starch ($(C_6H_{10}O_5)$), but between them is a fundamental difference: in amylose the glucose monomers are linked by α-1,4-glycosidic bonds whereas in cellulose the glucose monomers are linked by β-1,4-glycosidic bonds as shown in Figure 2. This seemingly trivial difference has important physico-chemical consequences.

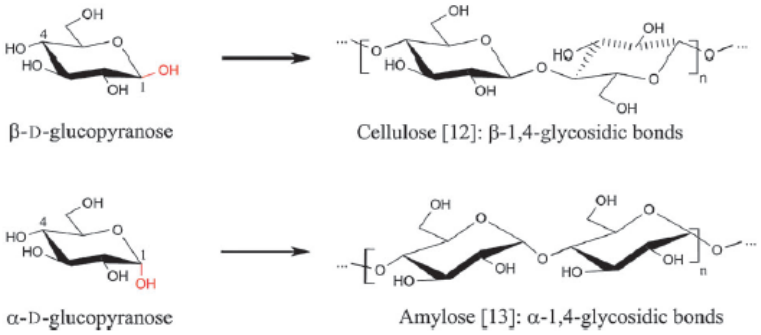


Figure 2. Structure of cellulose and amylose (starch) [2]

In cellulose, the glucose monomers are forced into a $^4C_1$ chair conformation, while succesive monomers are rotated over 180° around the polymer axis, to satisfy the bond angle of the bridging oxygen, as shown in Figure 3. This forces the hydroxyl and hydroxymethyl groups in an equatorial position, stabilizing the chair conformation and decreasing the flexibility of the glycosidic bond. As a result, the cellulose chain is linear, forming a rigid polymer, whereas amylose chains show more flexibility. Two intramolecular hydrogen bonds per anhydroglucopyranose unit further increase its rigidity. Every cellulose crystal phase exhibits a O3-H-O5` bond, as shown in Figure 3. In addition, another crystal phase dependent hydrogen bond is formed. Finally, the β bond is intrinsically more stable than the α bond, presented in amylose.

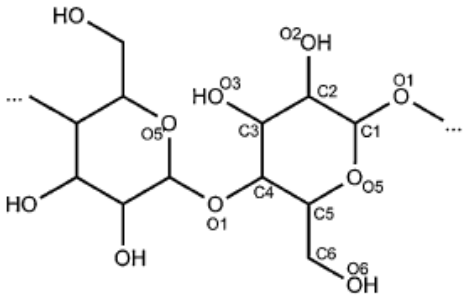


Figure 3. Position of C and O atoms in neighbouring glucose molecules in cellulose [2]

The hydroxyl and hydroxymethyl groups in cellulose chain protrude from the chain axis by virtue of their equatorial configuration. This makes them well suited for forming hydrogen bonds with neighboring cellulose chains and these interactions lie at the basis of the formation of planar cellulose sheets, which upon stacking form microfibrils. The microfibrils assembly spontaneously and constitute the cell wall of plants.

As recently revealed, an ordered multitude of weak CH–O bonds is at the basis of the affinity between the sheets, allowing formation of an ordered crystal network. The pattern of H-bonds in a cellulose crystal determines the internal cohesion, thereby determining its accessibility to catalysts and consequently its reactivity.

Whereas an individual cellulose chain is not significantly more hydrophobic than an amylose chain, crystalline phase formation makes cellulose insoluble in water and most organic solvents. The functional groups and glycosidic bonds are well protected by the microfibril structure, resulting in a half-life for non-catalyzed cellulose hydrolysis at 298 K between 5 and 8 million years. However, cellulose is not fully composed of crystalline domains. Between the crystalline domains of cellulose, amorphous areas/patches exist, which are much easier to hydrolyze. Molecular simulations estimated

the existence of 8 hydrogen bonds per unit cell in cellulose crystals and up to 5.3 hydrogen bonds per unit cell in amorphous regions. Crystalline cellulose may exhibit several crystalline phases, differing in the alignment of the cellulose chains relative to each other and therefore in the pattern of the H-bonds.

The natural form of cellulose is denoted as cellulose I and is the form present in microcrystalline Avicel PH-101 and α-cellulose, most often used in research. Cellulose I is a mixture of cellulose I_α (triclinic) and I_β (monoclinic) in varying proportions depending on its origin. Another form of cellulose, which is thermodynamically most stable and denoted as cellulose II, is formed from cellulose I by mercerisation (alkali treatment) or regeneration (solubilisation and subsequent recrystallisation). When celluloses I and II are treated with liquid ammonia other forms of cellulose are obtained, denoted as III_I and III_{II}, respectively. Celluloses IV_I and IV_{II} are formed by heating celluloses III_I and III_{II}, respectively. All these forms are presented in the Figure 4.

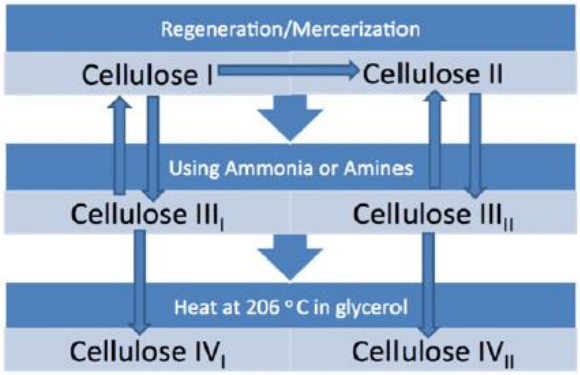
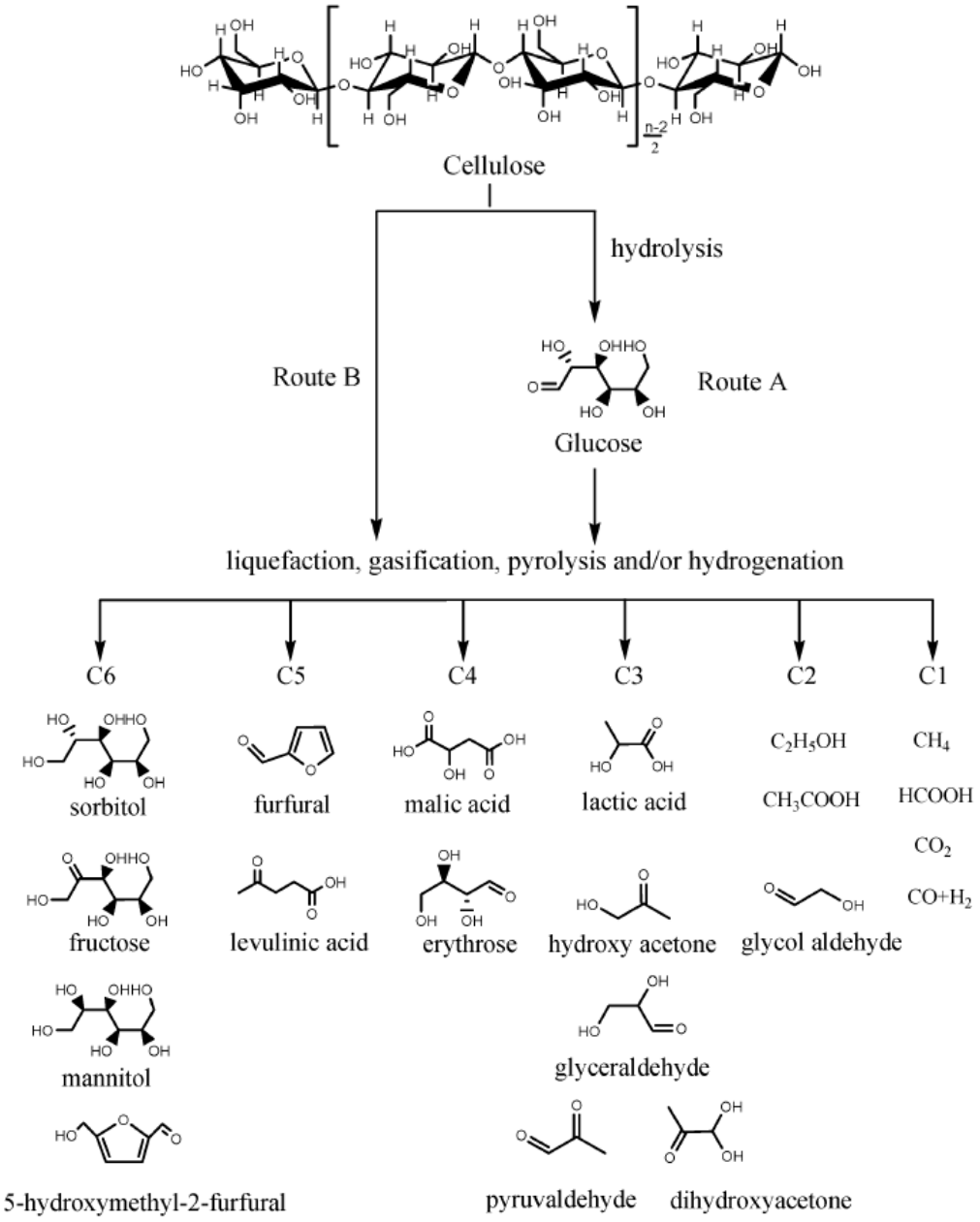


Figure 4. Interconversion of polymorphs of cellulose [4]

The main utilization of cellulose in industry is currently limited to textiles and paper manufacturing. In some biological processes such as fermentation and enzymatic catalysis, peculiar enzymes, bacteria and other microorganisms are used to break down cellulose molecules and thus a few commodity chemicals can be obtained. Nevertheless, such biological processes generally suffer from unsolvable problems such as low efficiencies, narrow reaction conditions and limited scale of production. Chemocatalytic conversion of cellulose [3] has been around for some time, but it only receives serious attention with the advent of a series of novel chemocatalytic reaction routes since the fossil oil crisis in the 1970s. Nowadays, researchers in all the world try to find ways to break down more easily cellulose and then transform it in useful chemicals. Some typical chemicals and fuels which can be produced by chemocatalytic conversion of cellulose by different chemical processes as presented in the Scheme 1 .



Scheme 1. Potential chemicals and fuels from the catalytic conversion of cellulose

Clearly, a variety of fuels, including ethanol, hydrogen, methane and chemicals such as glucose, fructose, sorbitol, levulinic acid and lactic acid can be obtained from catalytic conversion of lignocellulosic biomass. Lignocellulosic biomass can also be used to produce syngas ($CO + H_2$) which can then be transformed into fuels and myriad chemicals. In many instances, depolymerization and hydrolysis of cellulose to monomer glucose is regarded a necessary first step. Then glucose is further catalytically degraded into various intermediates, chemicals and fuels, following the A route.

Following the route B, it is desirable to obtain fine chemicals directly from cellulose, without having one more step implying the formation of glucose.

Compared to cellulose, hemicellulose has a very diverse composition [2] containing several pentoses (mostly xylose and arabinose), hexoses (mostly galactose, glucose and manose) and nonsugar compounds as monomers. The components of hemicellulose are presented in the Figure 5.

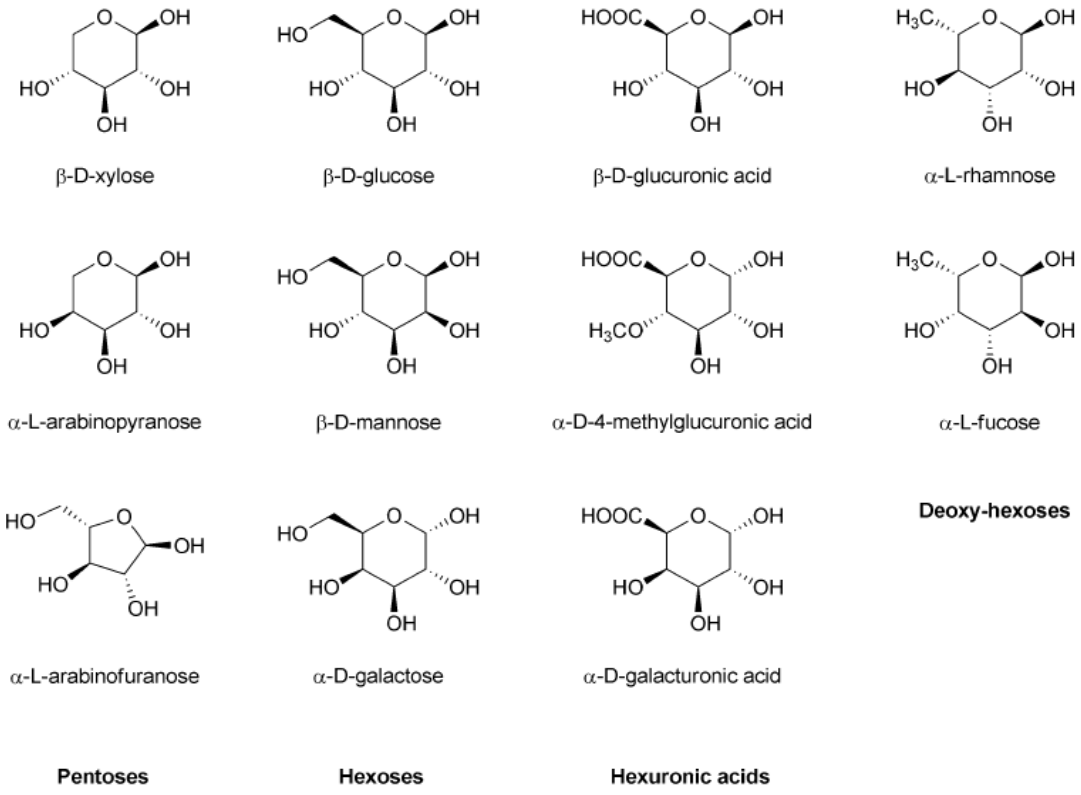


Figure 5. Structural building blocks of hemicellulose [5]

Furthermore, a typical hemicellulose chain is branched and shorter than that in cellulose, inhibiting crystal formation and making hemicellulose much easier to hydrolyse than cellulose. In cell walls, hemicellulose is associated with cellulose microfibrils via hydrogen bonds, forming a rigid structure functioning as the structural backbone of the cell wall. It is surrounded by a very resistant lignin sheath to protect it against chemical and physical stress and degradation.

The utilization of the saccharides derived from hemicellulose is essential for its efficient transformation to biofuels (mainly ethanol) or other high value-added chemicals. These two alternative purposes for hemicellulose valorization can be attained by chemical or biological conversion of the hemicellulosic monomers. Hemicellulose can be depolymerized into monomeric and oligomeric components with high purity and yield by chemical, enzymatic or thermal processes [6].

The most frequent physical treatment of lignocellulosic biomass is wood size reduction through mechanical means, to increase the accessible surface area available for further chemical or biological methods. However, thermal methods for biomass treatment can be considered attractive due to the fast rate of the conversion process and the broad range of allowed feedstocks. The most investigated example of thermal pretreatment is pyrolysis, which implies fast heating of biomass in the absence of oxygen to produce a liquid product (known as bio-oil) along with syngas and solid char. Pyrolysis is applied to the raw biomass (it does not require previous fractionation) and cellulose, hemicellulose and lignin are simultaneously converted to solid, liquid and gaseous compounds. Acid and alkaline hydrolysis are the two most reported technologies for chemical pretreatment of lignocellulosic biomass to obtain high sugar yields at low cost. Acid treatments favor hydrolysis of the hemicellulose fraction. Depending on the process and conditions used during the chemical pretreatment of lignocellulosic biomass, the fractionation process can result in the transfer of hemicellulose from solid to liquid phase, but degradation of the hemicellulosic sugars to weak acids, furan derivatives and phenolic compounds can also occur, as well as dissolution of chemicals derived from cellulose and lignin. Autohydrolysis, also known as hydrothermal pretreatment, employs compressed liquid hot water (temperature around 200°C and pressure above the saturation point) to convert hemicellulose into soluble saccharides with high yield and low byproducts formation.

The hydrolyzed hemicellulosic sugars can be transformed to a variety of chemicals, which must be considered primary substrates to obtain important industrial compounds. One of this compounds is ethanol. Second-generation ethanol, which is produced from lignocellulosic materials as feedstock, is an environmentally friendly renewable energy source. Once hydrolized, the fermentable sugars derived from hemicellulose could be used to produce ethanol [6]. The sugar mixture obtained after hydrolysis may contain xylose, arabinose, glucose, manose and other monosaccharides. Different microorganisms able to produce ethanol from pentoses have been identified, including bacteria, yeast and fungi. Furfural, an aldehyde of furan, is a highly versatile and key derivative from hemicellulose with diverse applications. Hydrogenation of furfural produces furfuryl alcohol, which is a useful intermediate for the manufacture of furan resins. These are used in thermoset polymer matrix composites, cements, adhesives, coatings and casting/foundry resins. Further hydrogenation of furfuryl alcohol leads to tetrahydrofurfuryl alcohol, which is used as a nonhazardous solvent in agricultural formulations and as an adjuvant to help herbicides penetrate the leaf structure.

Although furfural can be the starting block for the synthesis of a series of furan derivatives with high commercial interest, 5-hydroxymethylfurfural (HMF) is an even more attractive platform. HMF is

an organic product formed by the dehydration of hexoses, fructose being the most common carbohydrate used. Levulinic acid, 2,3-butanediol, xylitol and lactic acid are more examples of platform molecules that can be obtained from hemicellulose and which reveals the true importance of hemicellulose.

Lignin is another major component of lignocellulose, mainly present in woody biomass. It is a heavily branched and interconnected hydrophobic polymer consisting of three typical aromatic monomers: p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol presented in Figure 6. These alcohols polymerize by random coupling reactions, forming a very complex structure. In plant cell walls, lignin fills the spaces between cellulose and hemicellulose, and it acts like a resin that holds the lignocellulose matrix together [7]. Cross-linking with the carbohydrate polymers then confers strength and rigidity to the system.

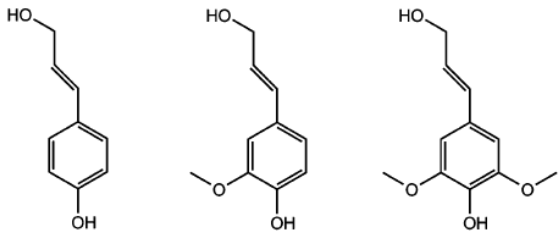


Figure 6. The aromatic monolignol monomers of lignin [2]

The structure and compositions of lignins depend strongly on the type of wool and on the part of the plant [5]. Lignin is extremely resistant to degradation. The reactivity of lignins is dominated by the substructures containing aryl esthers, biaryls, phenols, benzyl and aliphatic alcohols. Although the lignin fraction of biomass is usually burned to provide energy for the biorefinery, recently it has been advanced as a valuable source of renewable, aromatic platform chemicals viz. benzene, toluene, xylene, phenolics and alkane mixtures which are liquid at atmospheric pressure and ambient temperature.

Chitin is the most abundant biopolymer after cellulose, but it has not been fully utilized yet especially because it contains nitrogen and in this way it is hard to obtain chemicals that contain C, H and O. However, organonitrogen chemicals have been widely used in many fields, including medicine, agriculture, biodegradable materials and so on. Due to 7 wt% biologically fixed nitrogen, chitin is considered to be an ideal substrate for the production of value-added organonitrogen compounds avoiding the involvement of the energy-intensive Haber-Bosch process. Chitin is a structural polysaccharide comprising chains of modified glucose linked by β-1,4-glycosidic bonds. The main monomer in chitin is N-acetyl-glucosamine (NAG). The deacetylation of chitin produces chitosan. The

main monomer in chitosan is glucosamine (GlcN). Both chitin and chitosan are typical N-containing biopolymers and their structures are similar to that of cellulose. Due to the high safety, both NAG and GlcN are good candidates of food additives, cosmetics and pharmaceuticals. Some chitin-derived chemicals, like amino sugars, amino alcohols, amino acids and heterocyclic compounds, have shown potential application in medicine, food, beverages, cosmetics and others.

Another important part of biomass are fats and vegetable oils. They are mainly composed of triesthers of fatty acids and glycerol. However, mono- and diglicerides are also found in these feedstocks. Usually, seeds of plants and animal fat are the main sources of triglycerides. Free fatty acids and phospholipids are important ‘‘impurities’’ of these raw materials that can poison solid catalysts. Although biodiesel has attracted increasing attention, fats and vegetable oils can be transformed into a number of other products just by exploiting the reactivity of these sites.

Glycerol or 1,2,3- propanetriol (known as glycerine) is an organic molecule belonging to the class of polyalcohols. First it was isolated in 2800 BC by heating fats in the presence of ash, in order to produce soap.[8] Since the late 1940s, and following the discovery of synthetic surfactants, glycerol has been produced from epichlorohydrin, obtained from propylene as large chemicals companies forecasted a glycerol shortage and initiated its synthetic production. Today, some glycerol plants are closing and others, that use glycerol as a raw material, are opening due to the large surplus of glycerol that is formed as a byproduct in manufacturing biodiesel fuel. Biodiesel, which is a mixture of methyl esters of fatty acids, is produced from vegetable oils by transesterification with methanol. As a by-product, 1 mol of glycerol is produced for every 3 mol of methyl esters, which is equivalent to approximately 10 wt% of the total product [9]. So, it is expected that glycerol will reach an annual scale of 3.7 million metric tons[10].

Although glycerol could be burnt as a fuel, it could also be processed into more valuable components. One alternative is to etherify glycerol with either alcohols (e.g. methanol or ethanol) or alkenes (e.g. isobutene) and produce branched oxygen containing components, which could have suitable properties for use for example in fuel or solvents [9]. When glycerol is etherified with isobutene some or all hydroxyl groups in the glycerol molecule react. This will lead to the formation of as much as 5 isomers. In addition to etherification, oligomerisation of isobutene to C_8, C_{12} and C_{16} hydrocarbons occurred.

Because glycerol on its own is a low-value chemical whose production far exceeds the current demand, extensive research activities have been devoted to converting glycerol to value-added chemicals, following oxidation/dehydrogenation, dehydration, hydrogenolysis, steam reforming and

transesterification pathways. In industry, the major directions of valorization of this so called platform molecule are presented in the Figure 7.

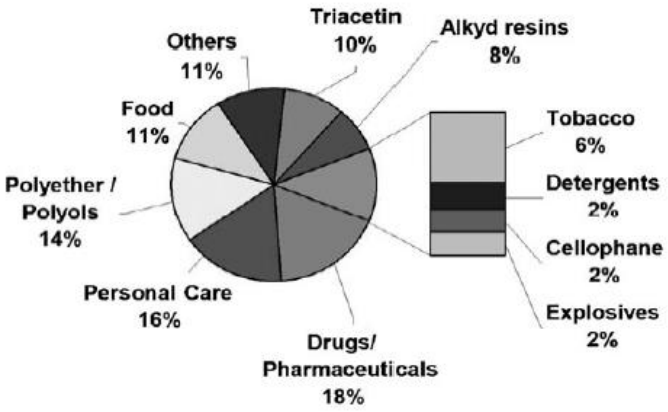
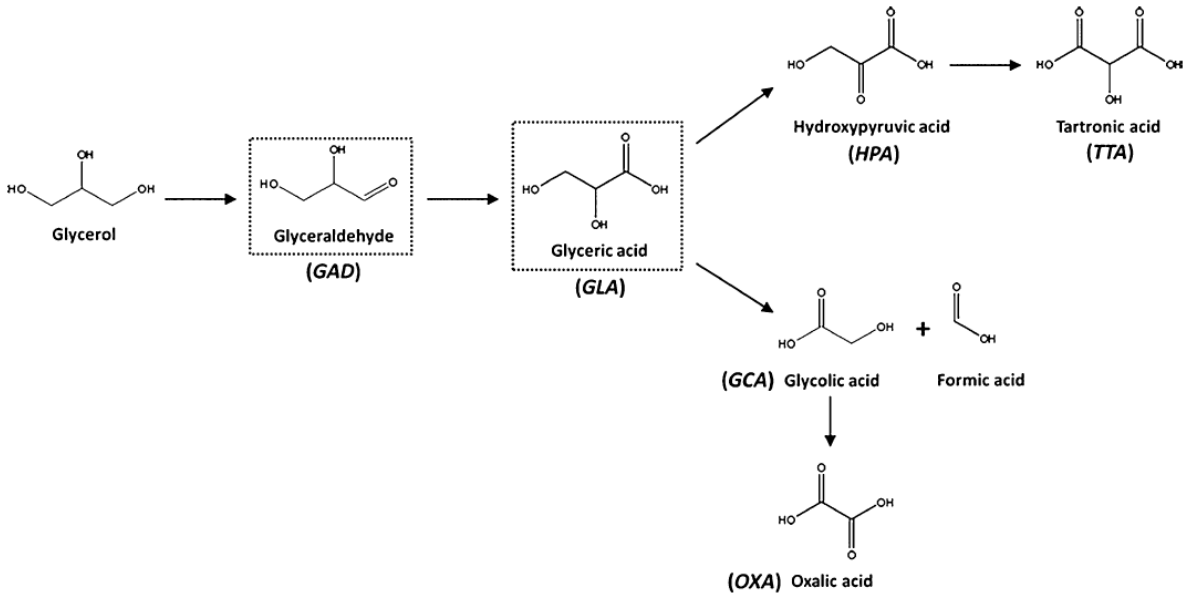


Figure 7. The market for glycerol (volumes and industrial use) [8]

An advantage of using glycerol in fuel is that, as a biocomponent, it could be included in the renewable category and help to meet the target of the EU directive which stipulates that traffic fuels should have contained 5.75% of components produced from renewables (biocomponents). In the oxidation pathway, glycerol can be converted into a series of compounds with different degrees of oxidation. As shown in Scheme 2 8 glycerol oxidation by electrocatalysis [11] produces a number of products including glyceraldehyde (GAD), glyceric acid (GLA), hydroxypyruvic acid (HPA), tartronic acid (TTA) and oxalic acid.



Scheme 2. Proposed reaction pathways for electrocatalytic and catalytic glycerol oxidation [11]

Electrochemical conversion technology has been used to produce a wide range of products from electrocatalytic dehydrogenation and reduction of biomass-derived oxygenates. This technology uses oxidation chemistry and proton exchange membrane (PEM) technology to electrocatalytically convert biomass-derived oxygenates into renewable fuels and chemicals. All the reactions in the PEM technology take place in one simple reactor that could be scaled up to a commercial level, which is a great advantage. Two recent papers [11] reported the production of dihydroxyacetone (25% yield) and lactic acid (34.7%) from the electrocatalytic oxidation and hydrothermal electrolysis of glycerol. Dihydroxyacetone and lactic acid are two molecules with major implications in the chemical industry because they can be chemically converted to other valuable products.

Glyceraldehyde is used as an ingredient of cosmetics. Further oxidation of glyceraldehyde produces carboxylic acids such as glyceric acid. These carboxylic acids can be converted into various products such as polymers and biodegradable emulsifiers. In Figure 8 are presented other chemicals that can be obtained using glycerol as reaction substrate [8].

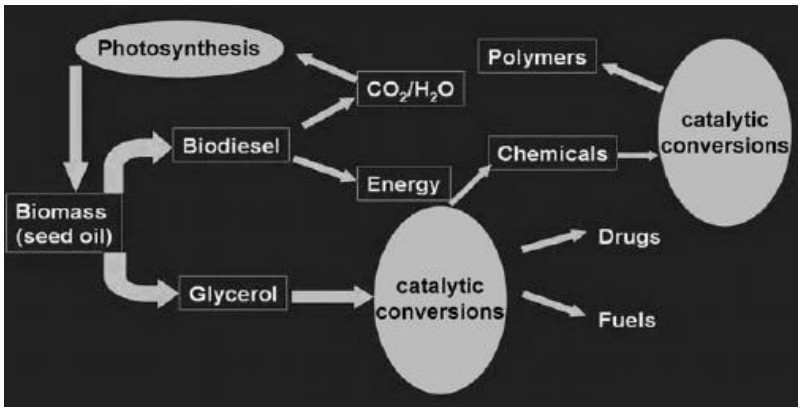


Figure 8. The chemistry of glycerol will play a crucial role in future biorefineres, in which materials and energy will be produced from renewable raw materials [8]

The dehydration pathway is useful to generate C=C bond-containing chemicals such as acrolein. Hydrogenolysis is applied to partially or fully remove oxygen from glycerol, offering propanediols, propanols, propylene glycol, et al. as products. Chemicals with more complex functionalities, such as lactic acid, may be produced when two or more catalytic functionalities are introduced into the same catalyst. From lactic acid alanine can then be produced which is an aminoacid in highly demand. Of the many options, the conversion of glycerol to bio-based aromatics (benzene, toluene and xylenes – abbreviated BTX) is considered an interesting option. So, recently, S. He et al. [12] reported the catalytic conversion, via pyrolysis, of pure glycerol over an H-ZSM-5 zeolite to

BTX, obtaining an yield of 8.1 wt%. Although the yield is not so good, this method is a promising one if we think at the large market for BTX.

At the end of this Chapter, I would like to present 2 new approaches in the use of biomass in order to underline the importance of this renewable resource that is in our hands. Allied to the dwindling fossil feedstocks at every increasing prices, the conversion of crude oil products such as the primary products (ethylene, propylene, etc.) to either materials or other chemicals requires the use of co-reagents, such as chlorine and ammonia, and various process steps to introduce functionality such as amine ($–NH_2$) into the simple structures of the primary products. Conversely, many products formed in plants often contain this type of functionality. Therefore, it is attractive to exploit this to bypass the use, and preparation, of co-reagents as well as eliminating various process steps by utilizing suitable biomass-based precursors for the production of chemicals.

If one considers the enthalpy changes involving the conversion of naphtha [13] from crude oil to chemical products, naphtha has a calorific value of about 45 GJ per tone and requires the use of additional energy in the form of heat and electricity to produce a product with a significantly lower calorific value compared to the original fossil raw material. This is shown in Figure 9.

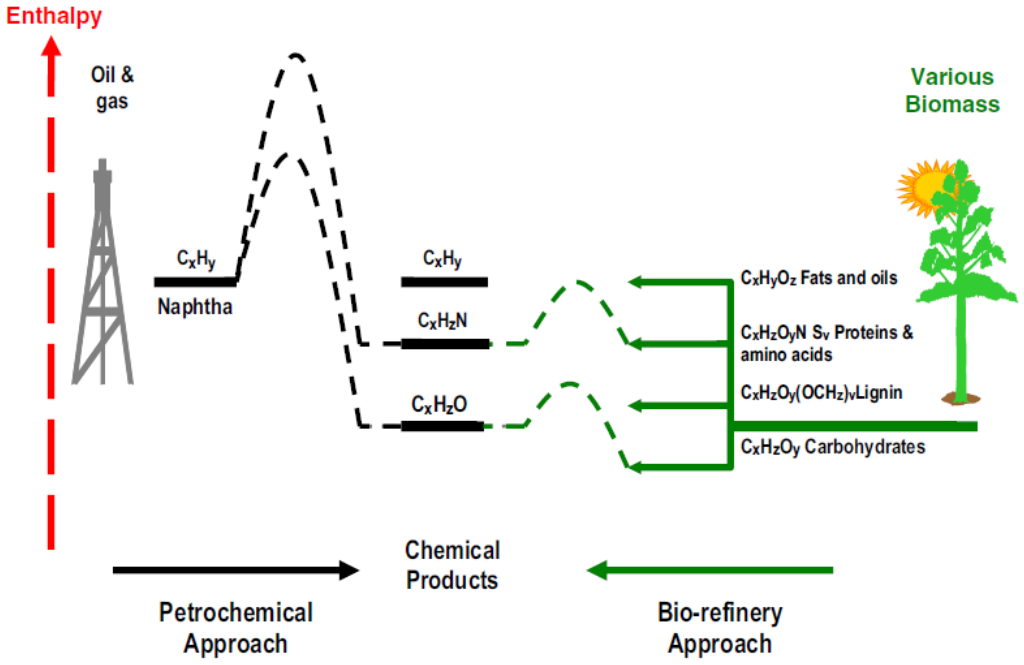
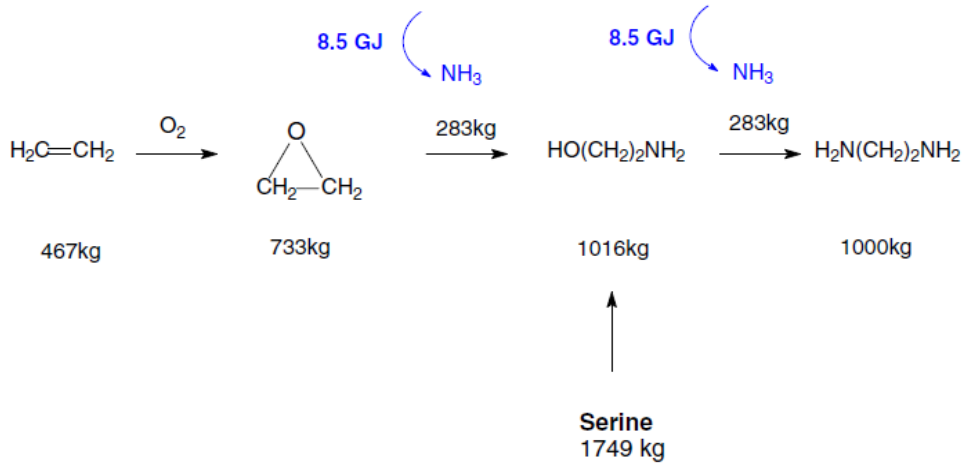


Figure 9. The use of biomass as a more energy-efficient raw material [13]

Another case study is the 1,2-ethanediamine synthesis – petrochemical versus amino acid route. 1,2-Ethanediamine or ethylenediamine is used in large quantities for production of many industrial chemicals. A most prominent derivative of ethylenediamine is the chelating agent EDTA, which is

derived from it via a Strecker synthesis, which is used as an chelating agent in the human body. Numerous bio-active compounds and drugs contain the N-CH_2-CH_2-N linkage, including some antihistamines [14]. Another important use of it is in the industry of polymers and the industry of dyes. Because the components of biomass have calorific values much lower than the one of crude oil they are preferred to be used in the synthesis of chemicals. For example, amino acids have a calorific value of about 20-30 GJ per tone and due to their chemical structures can be readily converted into amines, in fewer process steps and thus with a more limited input of energy [13]. 1,2-Ethanediamine is produced from ethylene by various routes. One implies the oxidation of ethylene to the epoxide, followed by amination to ethanolamine and then to 1,2-ethanediamine. A number of producers use a route via the chlorination of ethylene followed by substitution of the chlorine with ammonia. Starting from the amino acids serine this diamine could also be synthesized using well-described enzymatic and/or chemical conversion steps. Formation of the diamine is obtained by reaction of ethanolamine, obtained from serine, with ammonia, as shown in Scheme 3.



Scheme 3. Bio-based vs petrochemical production of 1,2-ethanediamine [13]

The current process for the production of 1,2-ethanediamine (via ethylene oxide) utilizes about 60– 70 GJ per tone where about 22 GJ is in the form of the ethylene raw material and, hence, about 38 GJ in the form of various process energies (including about 17 GJ for ammonia production). By utilizing the amino acid serine in the synthesis, various steps and process energies may be eliminated. On a stoichiometric basis, 1749 kg of serine is required to produce 1016 kg of ethanolamine. The calorific value of this amount of serine is about 26 GJ, based on a calorific value of 15 GJ/tone. In the described process, about 8.5 GJ for ammonia production, about 5 GJ for the conversion of serine to

ethanolamine, and a further about 5 GJ for the transformation of ethanolamine to 1,2- ethanediamine is required. This means a total of 18.5 GJ. Summarizing, the use of 26 GJ of serine saves about 41.5 GJ of fossil energy use. This represents an energy saving of about 41.5 GJ of expensive oil and gas resources. Bearing this in mind we can say with certainty that the future is represented by the valorization of the biomass in all industrial processes.

2. Heterogeneous catalysis for biomass valorization

2.1. Catalysts for the valorization of the biomass. Platform molecules

Biomass is a very valuable feedstock for the production of chemicals and in the same time of novel fuels, which in the future could replace crude oil and gas as the current major raw materials. The most interesting—since the most abundant—fraction of biomass is lignocellulose , shown in Figure 10.

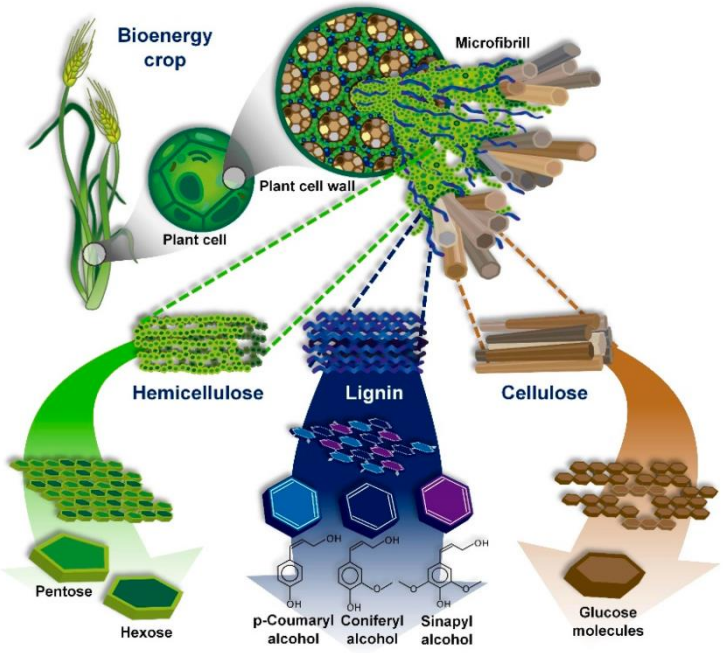


Figure 10. Structure of lignocellulosic biomass and its biopolymers; cellulose, hemicellulose,lignin [15]

Unfortunately, lignocellulosic biomass is very difficult to be hydrolized with the production of it's monomer components. Nevertheless, lignocellulosic biomass is highly protected and rather difficult to activate for further process steps [5].

Related to the activities connected to the biomass conversion, the biorefining concept was introduced not long ago and defined as a "facility that integrates biomass conversion processes and

equipment to produce fuels, power and chemicals from biomass" [16]. In principle, the biorefining concept is similar with today's petroleum refineries, the difference being the feedstocks. Regarding the polymeric components of lignocellulose, almost each carbon atom is connected to an oxygen. Because of this, in biorefineries, is necessary a controlled defunctionalization (e.g. reducing the oxygen content through efficient catalytic processes) rather than the functionalization used in the chemical industry so far. Unfortunately, this means that most of the developed processes in the petrochemical and chemical industry are not suitable for converting biomass, and alternative pathways for the production of fuels and chemicals should be developed. Moreover, for sustainable development and environmental protection reasons, an efficient biorefinery unit should provide a complete valorization of the biomass source, by performing the overall processes with a minimum loss of energy and mass, and should maximize the overall value of the production chain with the minimum formation of wastes.

Generally, a biorefining process consists of an efficient fractionation of the biomass into various value-added products and energy, using physical separation processes in combination with (bio) chemical and thermochemical conversion steps. Typically, three main units may be defined, as shown in Figure 11.

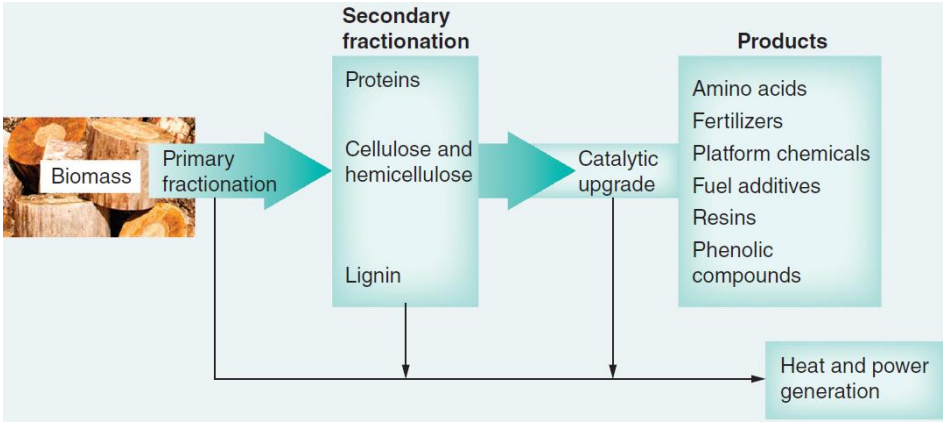


Figure 11. The main units of the biorefinery concept [16]

The primary fractionation unit is used for the separation of the biomass into its components by hydrolysis. Pretreatment or fractionation is an important tool to alter the structure of lignocellulosic biomass [15] in order to make the holocellulose (cellulose + hemicellulose) available for bioconversion. The main objective of pretreatment is the disruption of the physical barriers of the cell wall to depolymerize and to reduce the cellulose crystallinity. Regardless of the type of biomass, pretreatment has been identified as the crucial step, both technically and economically, in the bioconversion of lignocellulosic biomass for its use in biorefinery. The pretreatment method must have to be economical because both cost for operating and capital could be more than 40% of the total

processing cost. A large number of pretreatment methods for biomass, illustrated in Figure 12, have been studied. They can be broadly classified into: mechanical processes (refers to reduce particle size), chemical processes (using diluted acid, alkalis or organic solvents), physicochemical processes (steam explosion, hot water) and biological processes (use of microbial consortia or by enzymatic means).

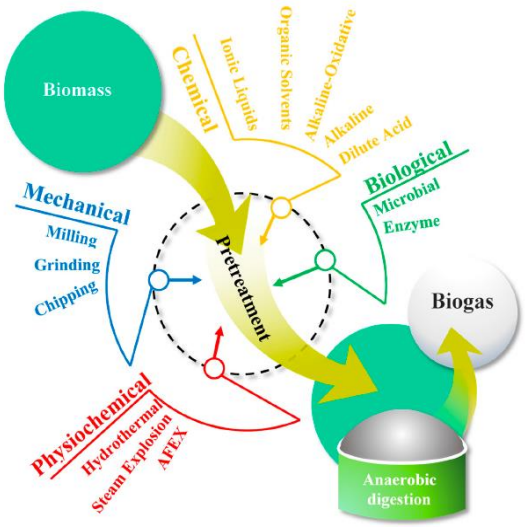


Figure 12. Pretreatment methods to increase the bioavailability of lignocellulosic biomass [15]

The mechanical pretreatment is the reduction of the particle size by methods such as milling, chipping, or grinding. Mechanical pretreatment is a well-known method to improve biogas production, however it is yet considered to be an expensive method, due its high energy requirements [15]. The size reduction of lignocellulosic biomass is an essential step to increase the accessible surface area and the porosity of the particles, besides reducing the crystallinity of the cellulose and improves the efficiency of the next processing step. One advantage of mechanical pretreatment is that it does not produce any secondary inhibitory substances, which suggest that could be suitable for methane production or any other bioprocess. It can be observed from literature that there is no universal particle size suitable for biomethanation process and it varies according to the type of the substrate and the process used for biomethanation. Dumas et al. [15] found negligible differences in biogas yield of wheat straw having the particle size in the range from 0.7 to 0.2 mm, and that the methane yield did not show any increase at particle size of 0.048 mm. On the other side, the processing time on particle reduction is not only important in energy terms, but also influence the efficiency of the bioconversion of lignocellulosic biomass. Rodríguez et al. [15] compared 30 and 60 min of mechanical pretreatment, and reported a 21% increase in methane yield for 60 min and that 30 min pretreatment did not improve the methane yield.

Chemical pretreatment of lignocellulosic biomass with acids, alkalis, and organic solvents are considered as one of the most promising, since they can be quite effective in degrading more complex-structured substrates. Furthermore they improve the bioavailability of carbohydrates by removing lignin and/or by decreasing the degree of polymerization and cellulose crystallinity. Chemical pretreatment has gained larger attention because usually it's less expensive and results in faster rates and better efficiencies in enhancing the degradation complex organic molecules. The main objective of dilute acid treatment is to achieve greater access to carbohydrate fractions of cellulose by hydrolyzing the hemicellulose. Low acid concentration at 0.2% to 2.5% wt and temperatures between 130°C and 210°C are employed, a common practice is the use of autoclave at 121°C for 1 h. [15] On the contrary, low temperature (room temperature) is used while using high reagent acid concentration (above 30% wt). High acid concentrations could cause corrosion problems and as a result high maintenance costs and further, generate inhibitor compounds at high rate and therefore increase the purification costs. Many studies confirmed that the dilute acid treatment is the most promising technology for lignocellulose pretreatment. Alkaline pretreatment shows high efficiency, especially in the delignification process. Alkaline pretreatment produces a swelling reaction in the cell wall allowing an increase in the internal surface area, and simultaneously decrease of polymerization degree and crystallinity of cellulose. To take full advantage of these alkaline effects, critical process parameter such as alkaline loading, reaction temperature, and quantity must be optimized. High concentrations of alkaline reagent lead to degradation and decomposition of polysaccharides. Low concentrations at low temperature and at atmospheric pressure are recommended . Furthermore, it does not generate toxic compounds such as furfurals and hydroxymethylfurfurals (HMF), and hence higher efficiency is observed in the biomethanation process. Although, there is still discrepancy on the choice of alkaline reagent, in terms of the greatest advantages, considering the cost of the reagent, performance, and manipulation, sodium hydroxide (NaOH) is preferred because it catalyzes under mild conditions, effectively attacks the linkage between lignin and hemicellulose in lignin-carbohydrate. In particular it cleaves the ether and ester bonds in the lignocellulose structure and also effective in the cleavage of the ester and carbon-to-carbon bonds in lignin molecules. However, sodium discharge might be environmentally harmful as they can lead to negative impacts such as soil salinization. KOH, although is three times more expensive than NaOH, it represents an alternative solution.

Organosolv pretreatment emerges as the only technology capable of isolating each component of the lignocellulosic biomass, attaining relatively pure lignin that can be sold as a by-product or converted into higher-value products in a biorefinery concept. Organic solvents such as methanol,

ethanol, acetone, acetic acid, peracetic acid, and so on are used with or without the addition of a catalyst reagent. The catalysts used include mineral acids (hydrochloric, sulfuric, and phosphoric acids) and organic acids (oxalic, acetylsalicylic, and salicylic acids). Although catalyst addition aids in higher pretreatment efficiency, use of a catalyst could have a negative impact on the environment i.e. chemical catalyst as acid causes acid-catalyzed degradation of the monosaccharides into furfural and 5-hydroxymethyl furfural, followed by condensation reactions between lignin and the reactive aldehydes. Acid catalysts are added in order to increase the rate of lignin removal and decrease pretreatment temperature, because acid catalysts cleave acid-labile bonds which help stabilization of lignin fragments. However, the use of chemical catalysts involves issues, such as equipment corrosion and the need of processing downstream effluents, resulting in high water consumption. Formic acid is a promising catalyst as it is believed to have fewer corrosive effects than stronger mineral acids and further to avoid production of inhibitors that are normally formed when acetic acid is employed. The organosolv process causes hydrolysis of the internal bonds in lignin and between lignin and hemicellulose. The organic solvents also cause hydrolysis of the glycosidic bonds in hemicelluloses and to a smaller extent in cellulose. The preferred conditions of organosolv process is generally in the following ranges: a cooking temperature of 180–195°C, a cooking time of 30–90 min and liquor to solid ratio ranging from 4:1 to 10:1.

Physicochemical methods are used to solubilize lignocellulosic components of the structure based on temperature and moisture content and to make the lignocellulosic material easily exposed for hydrolysis step and avoiding the formation of inhibitors. Although these methods are more complicated to implement, their significant effect on the pretreatment of lignocellulose feedstock promises high yield in the subsequent bioprocesses [15]. In general, physical pre-treatment requires greater energy expenditure, making it an expensive process and consequently not very profitable on an industrial scale.

The three main techniques used are: steam explosion, hydrothermal treatment and ammonia fiber explosion (AFEX). Steam explosion consists of exposure to hot steam for few minutes, followed by an explosive decompression of the biomass, which is effective in breakage of the fibrous rigid structure of straw and woody biomass. To facilitate auto hydrolysis reactions, the biomass is treated with saturated steam at a temperature of 160–260°C and at a corresponding pressure of 0.69–4.83 MPa for several seconds up to few minutes. The difference between pretreatment with steam and the explosion with steam is the rapid depressurization and cooling of biomass at the end of the steam explosion, which causes hydrolysis of hemicellulose into water soluble oligomers or to individual

sugars. Of late, hydrothermal pretreatment has gained importance, as it is efficient in penetration of the biomass, cellulose hydration, and removal of hemicellulose and part of lignin. The major advantages are that there is no requirement of chemicals and corrosion-resistant material for the reactor. Typically, it can remove most of hemicellulose and part of lignin in biomass by degrading them into soluble fractions and loosen the recalcitrant structure as well.

The temperature is the most important factor influencing the pretreatment. Typically, hydrothermal pretreatment is conducted in range of 90–260°C. AFEX is a physicochemical pretreatment under varying water loading, ammonia loading, reaction temperature, and residence time. In this pretreatment, liquid ammonia and the steam explosion processes are applied. The advantage of this process is that it does not require small particle size for efficiency and further, inhibitors are not formed during the process. However, the limitation is that less efficiency has been reported in the pretreatment of high lignin containing biomass [15].

Biological pretreatment offers an alternative choice to replace chemical pretreatment. However, its very slow reaction rate is unattractive from commercial point of view. Different microorganisms are used for lignocellulose pretreatment, such as white, brown and soft rot fungi. Although brown rot fungi participates in lignin decomposition, white rot fungi are well known and most effective microorganism for delignification process. In general, most of the fungi degrading lignocellulose secrete accessory enzymes like cellobiose dehydrogenase, aryl alcohol oxidase, glyoxyl oxidase, copper oxidase and hydrolytic enzymes, which cause the simultaneous or selective degradation of cellulose and hemicellulose along with lignin. These enzymes provide free radicals and intermediates that help in lignin and polysaccharide degradation. Although fungal pretreatments of lignocellulosic biomass are environmentally and economically friendly it is a relatively time-consuming process and Liu et al. [15] observed that a special bioreactor should be designed to create aerobic and aseptic conditions for fungal pretreatments. Microbial pretreatment, when compared to enzymatic pretreatment, demonstrates much better outcome in anaerobic digestion process due to their higher functional diversity and tolerance to environmental factors i.e. temperature and pH. Enzymatic pretreatment by using oxidative and hydrolytic enzymes produced by bacteria and fungi such as exo-, endo- glucanases, cellobiase, xylanase, pectinase and ligninolytic enzymes such as laccase, manganese, is advantageous in comparison to bacterial/fungal pretreatments. The enzymatic pretreatment method is gaining more interest due to the relatively short reaction time and the low nutrition requirement for the enzymatic reactions. In addition, the enzymatic pretreatment does not require expensive equipment for the processing. However, the activity of the enzymes and the efficiency of their reactions depends on

several factors including the composition of the lignocellulosic substrate, temperature, pH, incubation time, and bioreactor configuration. Additionally, the high enzyme cost remains a challenge facing the economic feasibility of this pretreatment methods for improved biogas production at an industrial scale. As a conclusion, biological pretreatment shows an increase up to 50% in comparison with untreated lignocellulosic biomass.

The secondary refinery unit is used for the conversion of the intermediate fractions to valuable end products (e.g. biofuels) and chemical intermediates, by using either thermochemical processes (e.g., gasification and liquefaction) or biochemical processes (e.g., fermentation). The third refining unit is used for the catalytic conversion of the chemical intermediates to high-added-value end products.

Solid catalysts are in principle very suitable for the processing of biomass. However, the requirements for biomass conversion are rather different, compared to the processing of hydrocarbon feedstocks, which form the backbone of our current energy and raw materials supply. A large number of technologies based on biological, thermal, and chemical processes have been developed for biomass valorization. Among those, chemical processing of biomass is of paramount research interest as the resulting products can exhibit relatively equating characteristics to petro-based products [1]. Various kinds of chemical processes, such as fast pyrolysis, hydro-processing, oxidation, dehydration, hydrolysis, transesterification, isomerisation, and many others have been reported, in which the application of a catalyst is crucial to enhance reaction rates and to obtain high yields of desirable products in a short time period. Indeed, catalysis is a key technology in modern chemical industry and plays an essential role in the production of a vast majority of bulk and commodity chemicals. Catalysis greatly contributes to the development of new, greener, and potential chemical processes, offering feasible alternatives to stoichiometric reactions, thus acting as a driving force towards a more sustainable chemical industry.

Homogeneous and heterogeneous catalysts are both used in petrochemical industry [1] as well as in biomass upgrading. Homogeneous catalysts, where the active sites are in the same phase as the reactants, can interact efficiently with the reaction substrates, typically resulting in higher turnover frequency (TOF) rates compared to heterogeneous catalysts. However, homogeneous catalysts are often associated with high toxicity, corrosivity, energy-intensive separation and purification procedures, and inefficient reusability. Stringent government regulations have therefore directed chemical industries to search for alternative catalytic materials. In this respect, heterogeneous catalysis, where the catalyst exists in a different phase (typically solids) as the reactants (mostly liquids or

gasses), could offer tremendous potentials for several energy and environmental-related applications including biomass upgrading. Availability of facile preparation methods, low production costs, remarkable robustness, high resistance to common reaction conditions (moisture, air, pressure, and temperature) and durable lifetime are some of the primary advantages of heterogeneous solid catalysts. More importantly, solid catalysts can be efficiently recovered from reaction mixtures and can be readily reused in multiple catalytic cycles, making the process cost-effective and more sustainable. Separation processes represent more than half of the total investment in equipment for the chemical and fuel industries [5]. It is not overstatement that the separation costs are a decisive factor in the final analysis of a new process. So, the ease of separation of solid catalysts can be a crucial advantage. However, it is necessary that these catalyst have high selectivities in order to guarantee the cost-effectiveness of the process.

If we talk about the usage of solid catalysts (heterogeneous catalysis) we need to bear in mind that are quite a few challenges face ahead in the design of these. Some of these challenges are: the discovery of new reaction media, the optimum catalyst composition, the porosity of the catalyst and the active sites presented by last. The necessity of novel reaction media appeared due to the polymeric nature of biomass. A number of mechanism protects these polymers against chemical and biological transformations. Due to this protective mechanisms, lignocellulosic materials lack solubility in most of the polar solvents. Although solvent-free operation is the best option for ‘‘green’’ processes, most of the biomass materials are solids, thus requiring at least a dispersant as reaction medium. The sluggish solubility of biomass components often makes the reactions heterogeneous concerning the substrate itself. In this case, processes on the substrate surface will affect reaction rates. A breakthrough was made recently by Rogers et al. [5]: alkylmethylimidazolium ionic liquids can dissolve cellulose or even wood. The dissolution process disrupts the fibers of cellulose, leaving the hydroxyl groups and β-glycosidic linkages accessible and thus improving their reactivity to other reagents.

Regarding the solid catalysts, the effect of the ionic liquid species on the catalytic activity is still an open question, due to the lack of studies in this field. However, it is known from other systems that halide ions are potent modifiers of the acidity and catalytic activity. Both BF_4^- and PF_6^- can hydrolyze, forming HF, under certain conditions, which is surely a very potent poison for silica and alumina-based materials. Additionally, the organic ions can also interact with supported metal catalyst changing the catalytic activity, selectivity or even promoting the leaching of metal species.

Solid catalysts are nowadays selected to be highly temperature-stable, because conversions proceed often in the gas phase at high temperature and to be resistant against relatively non-polar

compounds, since the basis of the chemical industry are hydrocarbons. These characteristics immediately lead to the choice of inorganic oxide materials, which meet both of these requirements. Polymeric catalysts and catalyst supports are otherwise much less suitable for the oil-based chemical industry, because the temperature range for their use is limited and there are substantial swelling and stability problems in organic solvents. Most biomass conversion processes, with the exception of the important route via pyrolysis/gasification of biomass, typically take place at moderate temperatures, and in the liquid phase, mostly in polar solvents. This places new requirements on the properties of solid catalysts. They need to be stable against dissolution and leaching in aqueous or highly polar media under different pH conditions. In addition, many of the biomass components possess strongly chelating groups, which can facilitate leaching and poisoning of the catalytically active phases. Very careful choice of catalyst components is therefore mandatory, and the diversity of biomass will make this problem even more severe. Furthermore, the resistance of the solid catalysts against polar solvents is another significant issue, since the chemical processing of biomass should mainly be carried out in liquid phase because of the polymeric nature of most biomass components. Having these points in mind, one may expect a shift of the solid materials used in biomass conversion towards polymeric organic solids, although inorganic solids will definitely continue to have major importance. Nevertheless, organic polymers or organic/ inorganic composites could have quite interesting properties in biomass conversion processes, since they allow wide variation in surface functionality and can be tuned between hydrophobic and hydrophilic behavior.

Porosity is one of the most important properties of solid materials, crucial for many practical applications, such as absorption and catalysis. These pore systems are often necessary to create sufficiently high surface areas needed for high activity. According to the IUPAC definition, porous materials are classified in three groups—microporous (pore size < 2 nm), mesoporous (2–50 nm), and macroporous (>50 nm) materials. Rationally designed porosity has been extensively exploited in many catalytic processes in the chemical industry. For instance, zeolites play an important role in cracking of crude oil and subsequent transformation of the fractions. These mixtures have very complex composition, but their selective transformation to important intermediates is possible, taking advantage of the well-defined micropore structure of zeolites and other molecular sieves. Generally, in porous materials most of the catalytic sites are inside the pore system. In this manner, the molecular dimensions of reagents, products or transition-state can control the reaction selectivity, as shown in Figure 13.

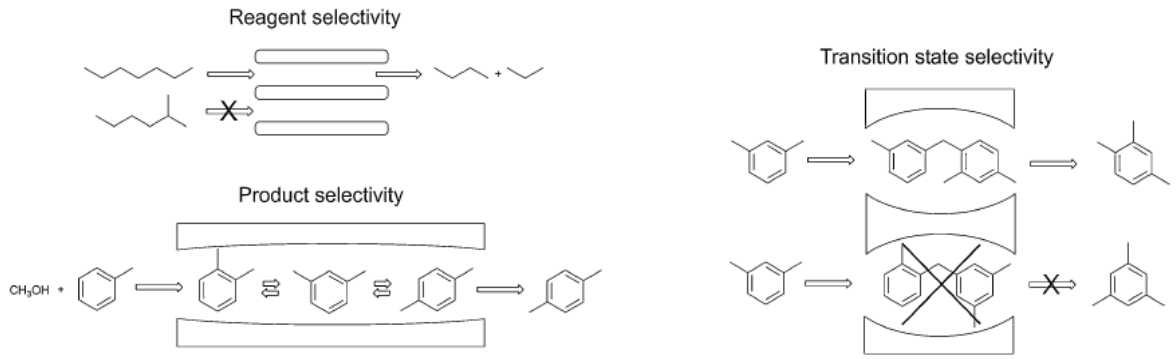


Figure 13. Shape selectivity in zeolite channels [5]

For instance, reagent selectivity occurs when only one type of reagent molecule can be transported into the pores. If several products with dimensions close to the pore sizes can be formed, only the molecules with proper dimensions to diffuse out will appear as observed products (product selectivity). Furthermore, the restricted space inside the pore system can prevent the formation of certain transition states that require more space than available, preventing the formation of several other products (transition-state selectivity). The most abundant components of biomass have high molecular weight and are not soluble in conventional solvents. Both characteristics make the transport of biomass molecules into pores very difficult and challenging. The molecular dimensions of individual sugar molecules are rather small: for instance, β-glucose has a length of 0.58 nm along the axis C-1 and C-4. However, expanding this dimension to a single chain of cellulose containing 1000 anhydroglucose units, a length of 580 nm is found. Of course, in solution, such macromolecules are never fully extended, and diffusion of chain-like molecules in pore systems is possible by a reptation process. Nevertheless, for the processing of polymeric biomass severe mass transfer limitations have to be expected, requiring careful selection of the materials and tailoring of the pore sizes. Moreover, if the lignocellulosic materials are insoluble in the reaction medium, such as water, a dispersion of two solids (substrate and catalyst) is observed. In these cases, even if the individual cellulose chains would be able to enter the pore system of the catalyst, almost no interactions between substrate and catalyst are expected, since the solid particles of the substrate, consisting of polymeric chains, would not be able to enter the pore system.

On the market there are available a wide range of catalysts that convers biomass intro valuable chemicals. Carbon materials have emerged as promising catalyst supports as well as metal-free active phase catalysts for various biomass transformation reactions [1]. They exhibit a broad spectrum of crucial catalytic properties such as large specific surface area, tailorable porous structures and surface

chemistry, excellent chemical stability in acid or base media, remarkable hydrothermal stability, and efficient functionalisation. Many types of conventional carbon materials, such as activated carbon, carbon black, glassy carbon, pyrolytic carbon, and polymer-derived carbon have been employed for stabilizing catalytic active phases. Owing to high specific surface area and rich surface chemistry, these carbon materials allow the formation of highly dispersed metal particles (Pd, Ru, Ni, Cu, Ag, Fe, etc.) throughout the catalyst matrix, resulting in enhanced resistance to sintering even at higher metal loadings and elevated temperature conditions. Advances in materials science and nanotechnology have provided several innovative strategies for the development of new carbon materials, such as carbon nanotubes, graphene, and mesoporous carbons that can be used as catalyst supports or active catalysts. We will talk here mainly about carbon nanotubes due to their unique properties exhibited in the conversion of biomass.

Carbon nanotubes (CNTs) are characterized by a hexagonal arrangement of sp^2 carbons with well-controlled cavity geometries. CNTs can be classified as single-walled and multi-walled CNTs based on the number of carbon layers present in the tubular wall. Single-walled CNTs are semiconductive with diameters of around 0.4–2 nm, whereas multi-walled CNTs are metallic. Interestingly, the cavities of CNTs can prevent the aggregation of active metal nanoparticles (NPs) during catalyst synthesis or catalytic reactions. Defect sites and surface chemistry are the key parameters that determine the catalytic efficiency of carbon materials in biomass conversions. For example, defect sites incorporated into the sp^2 framework of CNTs, graphene or activated carbon can strongly influence surface properties and catalytic functionalities. Heteroatom doping is an appealing strategy, which exploits defect structures in carbon materials. Carbon nanotubes offer potential possibilities for stabilising metal NPs, metal oxides, acid–base functional molecules, and even complex hierarchical hybrids. CNTs exhibit defective sp^2 carbon surfaces and improved electron transport, which facilitates the interaction of active phases with the CNTs. In addition to preventing particle aggregation, the nanoscale confinement within CNTs can also control the diffusion of reactive species and their interactions with the active phases. These fascinating characteristics have been exploited in the field of biomass upgrading, in order to achieve improved conversion rates with high yields of desired products.

Metal–organic frameworks (MOFs) belong to an extraordinary family of crystalline porous materials with unique characteristics and versatile functionalities. They have found plentiful applications in various fields, including catalysis, sensing, luminescence, separation, gas adsorption, H_2 storage, and optical devices. MOFs contain two key building blocks: metal ions or metal–oxo clusters

and multidentate organic moieties. The unique nature of metal ions or clusters lattice nodes and organic moieties as linkers allow the formation of robust metal–ligand coordination frameworks with well-defined porous structures quite similar to those found in zeolites. The capacity to fine-tune pore geometries up to a mesoporous size range is a notable advantage of MOFs over microporous zeolites. This pore modification is feasible by selecting a suitable combination of metal ions and organic linkers as well as by tailoring MOFs synthesis parameters. Mesoporous structures can facilitate efficient diffusion of (bulky) biomass substrates towards unsaturated active metal centers in MOFs, thus overcoming mass transport limitations often encountered with microporous zeolites. To meet the requirements of a specific target application, properties of MOFs can be further tuned by anchoring desired active phases. Overall, MOFs are highly tunable materials, which led to more than 20 000 synthesized MOFs, described in literature up to date. In addition, the high crystallinity of MOFs assists to carry out thorough structure–activity relationship investigations as well as molecular simulations that can provide valuable implications for the rational design of new, high performing MOF materials.

Nanoscale metals, metal oxides, or combinations of both display excellent catalytic activities for a broad spectrum of chemical reactions. Tailoring the particle size, morphology and composition of metallic materials generates changes in their electronic and geometric arrangements, which could result in an improved catalytic activity. Hence, the properties of nanoscale catalysts can be dramatically different from the corresponding macroscopic bulk materials, potentially leading to unusual catalytic results. However, the separation and recovery of nanoscale catalysts from liquid phase reaction mixtures for subsequent recycling remains a great challenge. Although filtration or centrifugation are typically used for the recovery of solid catalysts, these post-reaction steps add cost to the entire production, especially in the case of nano-sized catalysts. A promising solution to tackle this issue is the application of magnetic catalytic nanomaterials. Owing to outstanding paramagnetic properties and inherent insolubility, magnetic catalysts can be efficiently separated from complex reaction mixtures using external magnets without affecting their activity and selectivity. Iron oxide based nanomaterials (mainly Fe_3O_4) are widely used magnetic catalysts in biomass conversions due to their low cost, facile preparation, and strong magnetic properties [1]. Related magnetic materials, such as γ-Fe_2O_3, spinel ferrites with a general formula $M^{2+}Fe^{3+}{}_2O_4$ (M = Co, Ni or Mn), Fe-based alloys (FeB, FeNiB, etc.), and iron oxide supported materials also show potential for catalytic biomass conversions. Overall, magnetically recoverable catalysts have demonstrated high efficiency in a wide range of ‘‘one-pot”, “multi-step’’ catalytic reactions, including oxidation, epoxidation, hydrogenation, hydroformylation, olefin metathesis, polymerisation, photocatalysis, and C–C bond formation reactions. Moreover, novel

applications in asymmetric synthesis, organocatalysis, Knoevenagel condensation, or CO_2 cycloaddition reaction have been developed.

2. 2.The valorization of platform molecules in biofuels and biochemicals

A prime objective in the catalytic conversion of lignocellulosic feedstocks is the improving of the catalysts efficiency and selectivity towards value-added products. However, the incorporation of compatible catalytic processes in the actual infrastructure of petrochemical industry plants requires biomass feedstocks to be converted into building block chemicals with fewer oxygenated groups. These building block chemicals, also known as "platform molecules", are molecules with multiple functional groups that possess the potential to be transformed into new families of useful chemicals. The most important 12 platform molecules that can be produced from sugars via biological or chemical conversions and can subsequently be converted to a number of high-value bio-based chemicals or materials are given in the Figure 14.

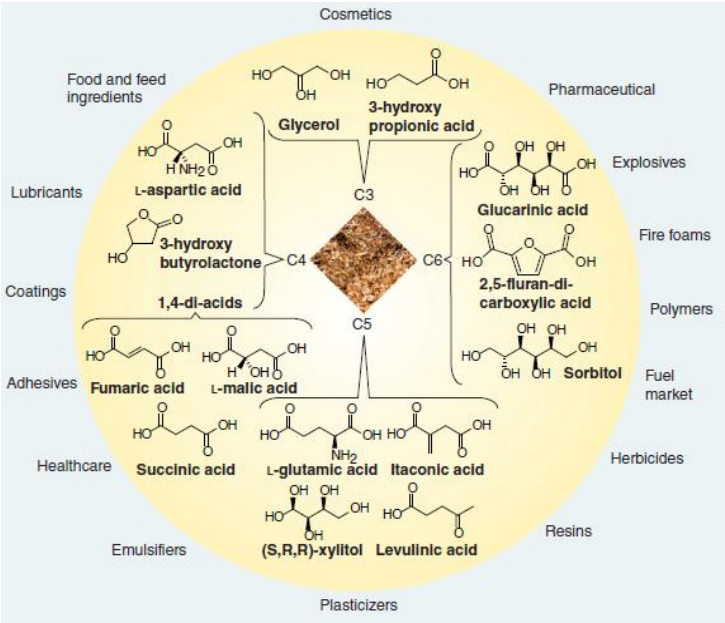


Figure 14. The 12 building blocks (platform molecules) identified in the biomass feedstock conversion [16]

More recently, Bozell and Petersen established a revised list of 15 top chemical including ethanol, furans, glycerol, lactic acid (LA), succinic acid (SA), hydroxypropionic acid/ aldehyde, levulinic acid (LA), sorbitol and xylitol [17]. Platform molecules such as pinenes and limonene are also available from terpenes and proteins. Moreover, according to Sanders el al. [16] vegetal proteins or distiller grains, available in large amounts as byproducts of carbohydrate fermentations, could become

a large source of amino acids that have a high potential as building blocks for fine and specialty chemicals.

Ethanol is the best-known platform molecule due to its enormous potential. This building block can be added to gasoline, which allows the fuel to combust completely in a more efficient manner. The ethanol obtained this way, consumes inexpensive feedstock and results in a net CO_2 reduction. Currently, bioethanol is mainly produced from starch-based material (grain or sugarcane).

The conversion of lignocellulosic biomass into ethanol encounters serious environmental problems, as shows in the analysis bellow [5]. In order to have an comparative analysis between the catalytic process and the usual one we have to bear in mind a descriptor called “E factor”, which is given by the ratio of mass of waste formed per mass of product. Although this concept does not capture the full impact of a process, since it does not take into account the quality of the waste produced, inspection of the E-factor can be illustrative in the analysis of a specific route. The dilute acid hydrolysis of wood followed by the fermentation of hexoses is able to convert about 11% of the energetic content of wood into ethanol [5]. Most of the energy requirement for production of ethanol from wood can be supplied by burning the lignin fraction of wood. Figure 15 shows the amounts of waste, byproducts and ethanol produced during this process.

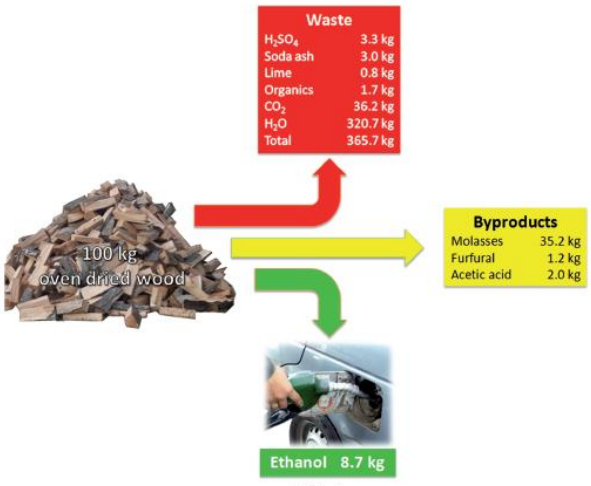


Figure 15. Ethanol by-products and waste formed in the two-stage dilute acid hydrolysis of cellulose followed by fermentation of glucose to ethanol [5]

The production of ethanol from wood generates 40.2 kg waste per kg of ethanol, placing this process at the level of waste generation as found in the production of fine chemicals, according to R.A. Sheldon’s classification [18]. For sake of comparison, the manufacture of bulk-chemicals has much lower E-factors, typically ranging from <1 to 5. Most of the waste generated in the ethanol production

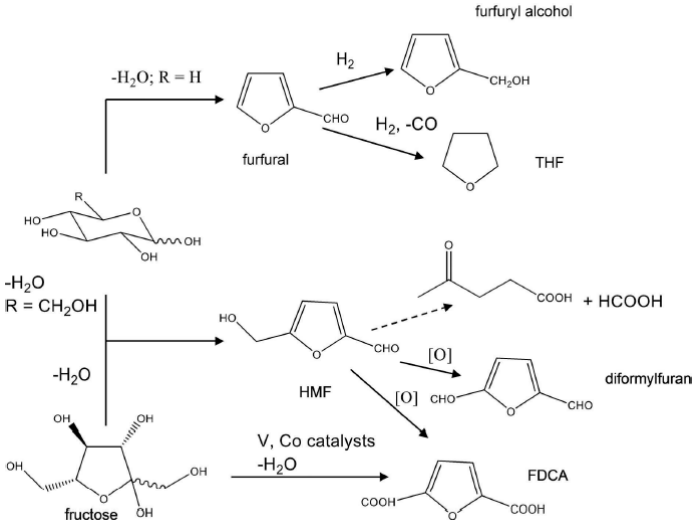
from wood is industrial wastewater. Regarding a large-plant of cellulosic ethanol with a capacity to process 10 000 tons of lignocellulosic material (wood, straw and other), producing 870 tons of ethanol a day, the amount of wastewater generated would reach 32.07×10^6 L. This amount is enough to supply a town in an industrialized area with cca. 300 000 inhabitants daily.

Although water is the most environmentally friendly solvent known, this statement is only valid when water is returned clean to the environment. In the case of the dilute acid process, several dehydration products, such as hydroxymethylfurfural (HMF), furfural, formic acid and even some phenols are formed. The concentration of some of these impurities has to go down to the ppm level for the proper reuse of water. In other words, high-cost advanced oxidation processes for the industrial wastewater cleaning are mandatory. Among several other reasons, this also makes cellulosic ethanol still much less cost-competitive to ethanol from sugarcane or even from maize. The biomass residues, such as sugar cane bagasse, can be used to supply energy for the biorefinery processes, reducing thus the emission of greenhouse gases. A fair estimation shows that ethanol produced from sugar cane emits 91% less CO_2 than gasoline, while this value is only 18% for ethanol from maize. In Brazil, most of the energy required for the production of ethanol from sugar cane is supplied by burning the sugar cane bagasse, producing heat and electricity. This makes ethanol from sugar cane almost neutral in CO_2 emissions.

Ethanol can serve as a feedstock to produce hydrogen via the catalytic steam reforming. This route has been regarded as an attractive feedstock due to its non-toxicity. This process is associated with the gasification of aqueous solutions of ethanol at high temperatures (typically from 600°C to 800°C), high availability, high hydrogen content and atmospheric pressure using metal oxides, mixed metal oxides, supported base metals (Ni, Co, Cu), and supported noble metals (Pd, Pt, Rh, Ru, Ir). However, it comprises several other simultaneous reactions (dehydrogenation, decomposition, dehydration, etc.). In order to overcome the energy-intensive distillation of this process, aqueous-phase reforming can be implemented to produce hydrogen at lower temperatures. Additionally, the catalyst stability (deactivation due to coke deposition) and control over formation of side products (e. g. acetaldehyde, acetone and ethylene) are negatively affected by the severe temperature conditions.

Nowadays, the acid catalyzed hydrolysis of pentoses and hexoses has increased in importance. The conversion of these sugars affords two highly interesting value-added chemicals: furfural (FUR) and 5-hydroxymethylfurfural (HMF). HMF can be completely or partially oxidized to 2,5-furandicarboxylic acid (FDCA). Besides homogenously catalyzed production to yield furanic compounds, current research addresses challenges mainly on the development of heterogeneously

catalyzed systems in pursuance of reutilization and ease to separate solid catalysts from the reaction medium, avoid corrosive and toxic effluents and can be synthesized with broad surface acidities and porosity properties to improve selectivities. On a parallel pathway, the development and application of ionic liquids (IL) onto these systems offers new advantageous perspectives. The direct use of furans such as FUR and HMF are considered excellent platform molecules and often called “sleeping giants” due to various potential applications, such as: promising additives in liquid fuels (especially 2-methylfuran and 2,5-dimethylfuran), monomers for various polymers (such as 2,5-hydroxymethylfuran, 2,5-carboxyfuran) and chemicals for value-added products The main advantage of the latter potential application is that a shorter process takes place, including intensified reaction conditions, to form these value-added chemicals. This route also requires less H_2 consumption, hence CO_2 emissions remain low, which leads to a high carbon efficiency. Moreover, FUR and HMF have not yet been involved directly as fuel components due to their chemical properties, such as melting points and stability. Nevertheless, they are attractive platform molecules for further synthesis into a variety of value-added furan derivatives. Scheme 4 shows the chemical pathway to form furan-based molecules using pentoses and hexoses as raw material.



Scheme 4. Synthesis and transformation of furans [19]

Furfural (2-formylfuran, FUR) is the dehydration product of C_5-carbohydrates (i.e. xylose, arabinose). Lignocellulosic biomass is uniquely suited for FUR production. More than 80 chemicals have been identified as direct or indirect derivatives of this building block coming from hemicellulose-rich feedstocks [19]. Currently, furfural is produced industrially, associated with a variety of environmental concerns, for instance toxic effluents originating from sulfuric or hydrochloric acid at

temperatures <200°C. Another issue is the high energy consumption related to the steam stripping process to avoid further furfural degradation and fuel employment to generate the steam. Besides mineral acids, organic acids have been shown to provide catalytic properties in FUR formation. The dehydration of xylose into FUR is associated with a significant challenge that promotes the formation of byproducts. An efficient approach to avoid this issue is the addition of an organic co-solvent, which would continuously extract furfural from the aqueous phase into the organic phase. Therefore, FUR would be protected in the organic solvent and hence avoid losses by humin formation, and furfural yield would be improved. Furfural can also be used directly as a solvent. The most important market (approx. 60%) of furfural is used to synthesize furfuryl alcohol (reduction at 120°C at atmospheric pressure). Furfuryl alcohol has application in the manufacture of foundry resins, component production of P-series fuels, liquid alkanes and in the food industry. Tetrahydrofuran (THF) and tetrahydrofurfuryl alcohol are two very appealing chemicals also formed from furfural that have wide applications in the chemical industry. The rest of the furfural market is mainly divided between the petrochemical, plastics and agrochemical industries and in pharmaceutical production. Other interesting compounds are 2-methylfuran (MF), dimethylfuran (DMF) and MTHF, which are formed via hydrogenation and can be used as biofuels. MF is typically employed continuously in the production of pesticides, perfume intermediates and pharmaceuticals. At present, MF is formed as a by-product in the formation of furfuryl alcohol from furfural. Even though MTHF has a lower octane number (87) than ethanol (108.6), MTHF shows more fitting biofuel aspects due to its hydrophobicity, it has a higher density and a higher heating value. Therefore it is employed with ethanol and gas to create an alternative fuel that can be used as a substitute for gasoline (P-Series Fuel). Furthermore, MTHF is a promising substitute for dichloromethane (DCM), a common solvent used in pharmaceutical and agricultural products and a probable carcinogen. Carboxylic acids can also be produced via oxidation from FUR. Furoic acid (employed in the pharmaceutical, agrochemical and cosmetic fields) and maleic acid (an important raw material employed in the manufacture of textiles, food additives, plasticizers, bulk-drugs and agricultural chemicals) can be formed from FUR adding O_2 as an oxidant.

Hydroxymethylfurfural (HMF) can be catalytically produced from biomass-derived hexose polysaccharides, as shown in the Figure 16. It can also be formed from cellulose, starches and most typically from hemicellulose-rich sugars (glucose). HMF formation from cellulose and starch implies the sequential process from glucan hydrolyzation to glucoses, isomerization to fructose and dehydration into HMF. This process is typically undertaken in homogenous catalysis employing

mineral acids or in heterogeneous catalysis using salts as cocatalysts and solid acid catalysts based on different methodologies such as polymeric resins and zeolites.

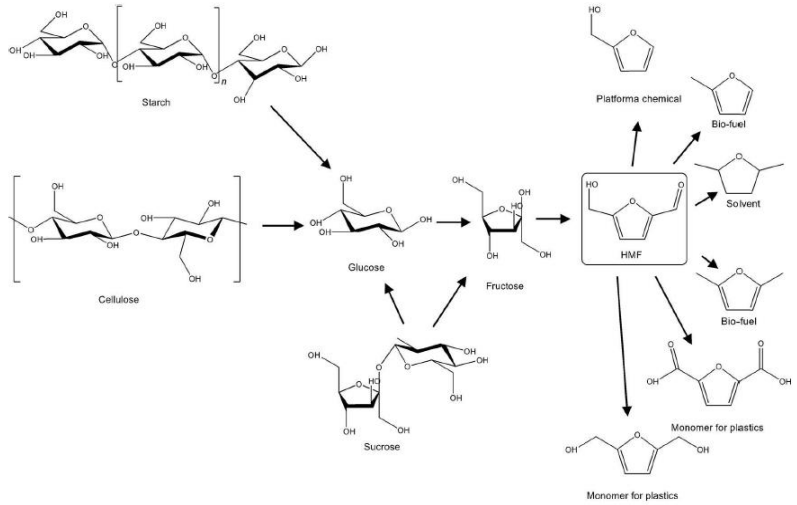


Figure 16. The synthesis of HMF from carbohydrates and its further derivatization to important chemicals [19]

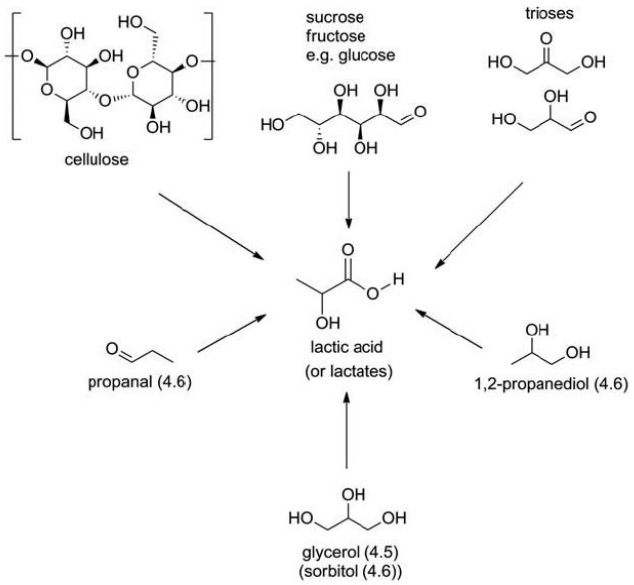
The flexible chemistry of HMF offers many possibilities and markets, due to its reactive structure comprising a furan ring, an aldehyde group and a hydroxyl group. Four main reaction paths to synthesize further chemicals from HMF have been identified: oxidation, reduction, redox and decarbonylation reactions. HMF, together with levulinic acid (LA) are the most interesting biochemicals formed from cellulose. Presently, HMF is employed as raw material to synthesize diformylfuran (DFF) and FDCA via oxidation. DFF is an attractive raw material for the production of pharmaceuticals, fungicides, furanic polymers, etc. 2,5- dimethylfuran (DMF), a high caloric biofuel derivative, is produced via reduction reaction [19]. In addition, many other valuable products have been identified via reduction such as furfuryl alcohol, 2,5-dihydroxymethyltetrahydrofuran, 5-methyltetrahydrofurfuryl alcohol, 2,5-dimethyltetrahydrofuran and furan-2,5-dimethanol (FDM). FDM can also be converted with 80% of yield using NaOH as reported previously via redox reaction. Another important compound formed via redox reaction is alkoxymethyl furanoic acid, which can be employed as a surfactant. Additionally, HMF could find use in the biofuel and pharmaceutical markets, in a similar way to that of ethanol. Furthermore, not only can a new generation of biofuels be formed from HMF, but also a broad range of intermediates and fine chemicals can be synthesized from it. For instance, another interesting route is the formation of levulinic acid and formic acid from HMF, both acids can be further transformed into biofuels and chemicals.

Furan-2,5-dicarboxylic acid (FDCA) is also a very attractive biobased platform molecule because it can be employed as a substitute for terephthalic acid and polyethylene terephthalate in the production of polyesters. Even though there exist several paths to afford FDCA, the majority of reactions take place via oxidation of HMF. This reaction path faces several challenges that include the formation of condensation products even at low temperatures (373 K) and the incomplete oxidation of HMF to FDCA, which causes the production of partially oxidized undesired compounds. As is the case with many chain processes, improvements in HMF formation favor production of FDCA. Currently, research on this field focuses on the development of bimetallic catalysts with a carefully designed size and composition that have proven to be promising in improving catalyst activity. (reference platform molecules) FDCA also finds wide-spread utilization as a feedstock to produce renewable plastics including bottles, food packaging and automotive applications. Currently, Avantium operates a pilot plant in the Netherlands to synthesize levulinics (methyl levulinate), alcohol (methanol) and FDCA from carbohydrates in two catalytic steps [19]. This process involves the dehydration of the bio-based sugar in an alcohol media to produce methoxymethyl furfural (MMF) instead of HMF, which would be produced in water. After MMF has been formed, it undergoes catalytic oxidation in acetic acid to yield FDCA.

Organic acids (ranging from C_1 to C_6) serve as an important class of renewable chemicals that are also obtainable from lignocellulosic matter. These acids include a compelling fraction which is obtained by a minimum number of process steps from industrial sugar-rich streams, and are very attractive as platform chemicals. In the past decade, significant developments in the valorization of biomass into organic acids have been observed including oxidation, anaerobic and aerobic systems, which represent a singular pathway to produce these types of platform molecules [19]. In comparison to various other routes of biomass valorization, the pathways involving organic acids production tend to neglect the use of expensive reagents such as H_2. Moreover, the transformation of lignocellulosic feedstock requires various enzymes and microorganisms to act in synergy, which is challenging, but presents a worthwhile opportunity to develop new routes and engineered strains to overcome these issues.

Lactic acid (2-hydroxypropanoic acid, LA) is a consolidated bioproduct in the world market due to the fact that about 70% of the LA market is used in the food industry. LA is an encouraging renewable building block for the development of biodegradable plastics and is an attractive feedstock to substitute current petrochemical-based materials [20]. As shown in Scheme 5, lactic acid is typically obtained via carbohydrate fermentation from C_6 sugars (glucose and fructose) after pretreatment with

acids or bases (about 90% of all LA produced worldwide) but it is also possible to synthesize LA via chemical routes, starting from propanal, 1,2-propanediol and glycerol.

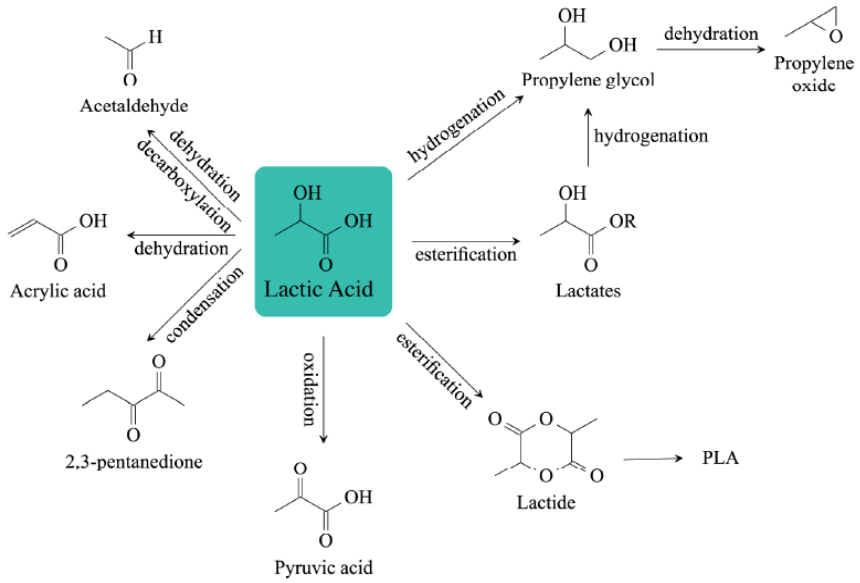


Scheme 5. Possible routes and raw materials for non-fermentative lactic acid synthesis [20]

The biochemical pathway usually takes 2–4 days and exhausts a significant amount of calcium hydroxide that is used to balance the pH value of the reaction medium, hence producing a large amount of waste. However, this route faces two main cost related drawbacks that are associated with sugars used as feedstock and sterilization. Aside from the costs associated with the production of LA, the development of high performance LA-forming microorganisms is a significant issue to be considered in developing strong long-standing LA biorefineries. Furthermore, an essential factor in developing strong LA biorefineries is related to the location of the site and to achieve sustainability over their fossil fuel-based counterparts. The chemical route faces several constraints due to the use of hydrogen cyanide (HCN) that forms lactonitrile and acetaldehyde, which are associated with environmental concerns.

Lactic acid is a versatile platform molecule due to its hydroxyl group and carboxylic acid group, and its price is declining as its commercial availability increases. As a highly promising platform molecule, LA and its derivatives are extensively employed in the food and pharmaceutical industries. New applications [19] have been recently intensified from this building block in the field of commodity chemicals such as propylene oxide and propanoic acid, liquid fuels and polymers. Among the polymers, one breakthrough has increased interest from several major corporations to synthesize biodegradable polylactic acid (PLA), which is biobased and compostable. PLA synthesis includes

polycondensation of LA monomers and the removal of by-products (water and alcohol) from the reaction medium. In Scheme 6 it can be seen some chemicals obtained starting from lactic acid as well as the specific routes [21].



Scheme 6. Lactic acid as a platform chemical [21]

LA has market demand in sectors that, theoretically, have very large-volume uses such as personal and home care, biodegradable plastics, food and beverages, pharmaceuticals and animal health. Three main manufacturers are leading the global market on LA production: Corbion-Purac in the Netherlands (supplying from food, chemicals and plastics to biomedicine and beyond), Galactic in Belgium (leading the development of sustainable LA production for food, feed, personal, healthcare and industrial markets and the giant chemical producer Cargill in the USA.

Succinic acid (1,4-dicarboxylic acid, butanedioic acid, SA), a four-carbon dicarboxylic acid is drawing considerable attention for its versatile chemistry due to its two carboxylic groups. SA is a colorless crystal, soluble in water, and one of the strategic building blocks that can be transformed into a diverse range of valuable chemicals. Succinic acid can be utilized for the production of detergents, surfactants, additives, pigments, resins, foaming agents, ion-chelator in the metal industry, biodegradable solvents, food and pharmaceutical products [19]. SA is normally produced by plants, animals (including humans) and microorganisms. Among these living organisms aerobic and anaerobic microbes present promising results in the formation of succinic acid. Due to the well-studied *E. coli* and the current available genetic tools high yields of SA are attainable. Genetically engineered microorganism strains can bring high yields of succinic acid. This has been successfully produced from

various biomass sources, such as wheat, corn waste, rapeseed, rice straw, bagasse and others. Succinic acid can also be synthesized via chemical routes including paraffin oxidation, catalytic hydrogenation or electroreduction of maleic acid or anhydride. However, current research has focused especially on the fermentative process of SA synthesis. Once succinic acid is formed, it can be feasibly subjected to esterification, amidation and hydrogenation in aqueous media. SA can also be readily converted to other bulk chemicals like 1,4-butanediol, GBL or THF as shown in Figure 17.

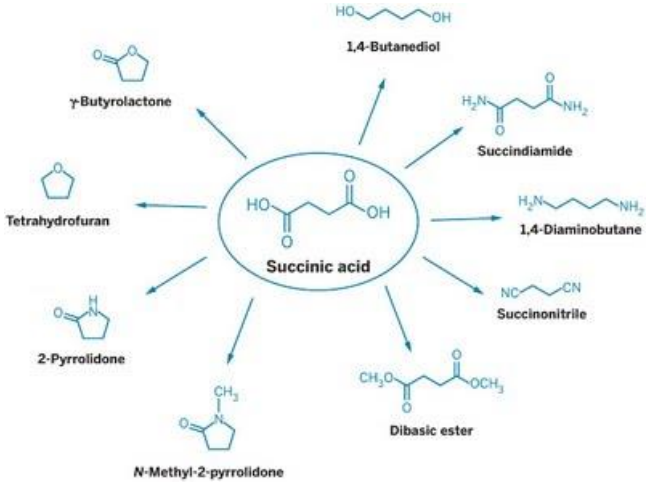


Figure 17. Valorization of succinic acid [22]

Levulinic acid (also named 4-oxopentanoic acid, LVA) is a highly promising chemical intermediate that can be converted to a variety of valuable chemicals. LVA is a valuable platform chemical demonstrating carboxyl and carbonyl functionalities that give a high grade of chemical versatility [19]. This gives levulinic acid advantages over other chemicals, since its versatile structure allows it to react both as a carboxylic acid and as a ketone. As a promising platform molecule, Levulinic acid is a starting material of various industrial applications, such as fine organic synthesis, animal feed and food as well as polymer materials, plasticizers, extenders for fuels, herbicides, solvents and coatings. LVA synthesis is achieved via dehydration of hexoses using an acid catalyst. Usually, to form levulinic acid from sugars, higher acid strengths and longer residence times are required than to form HMF. The main drawback of using mineral acids is the separation phase from the reaction medium. Thus, LVA can be obtained with a maximum theoretical yield of 72% from a hexose implementing base in the Biofine process due to its efficient reactor system and polymerization inhibitors. Researchers have also tried to replace homogeneously catalyzed systems with heterogeneously catalyzed systems with promising results when using glucose and fructose in aqueous solutions. As a versatile platform molecule, levulinic acid can be converted into fuels by a number of

catalytic routes combined with thermal deoxygenation reaction. The catalytic hydrogenation of levulinic acid leads to γ-valerolactone (GVL). This can be observed in Figure 18.

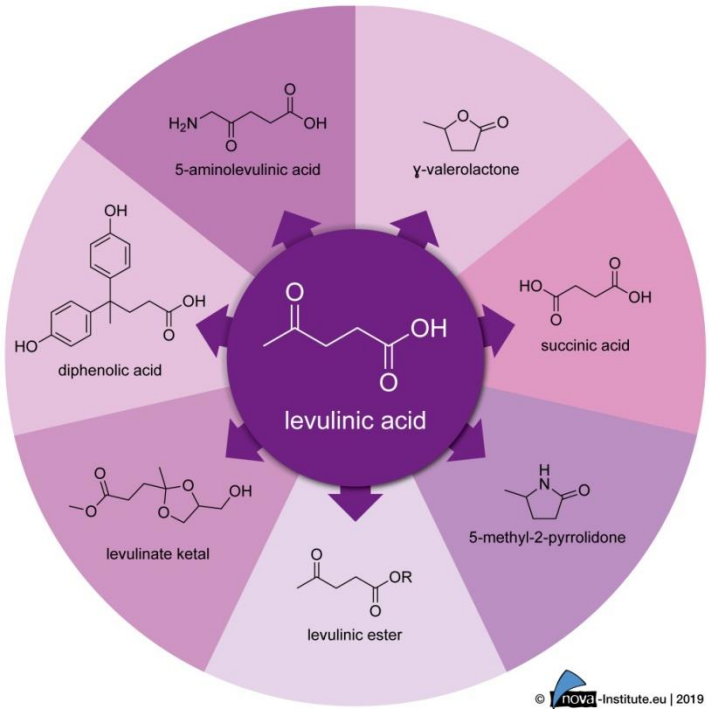


Figure 18. Valorization of levulinic acid [23]

γ-Valerolactone (GVL) is a value-added chemical and starting material to synthesize a broad scope of valuable chemicals [19] such as pentenoic and pentanoic acids, fuel additives, polymers and a stable organic solvent for biomass-based processes including MTHF formation. GVL is non-toxic and is stable at normal conditions in water and in the presence of air, which makes it an attractive biofuel component.

Sugar alcohols, also called polyalcohols, are obtained when the carbonyl groups of carbohydrates are hydrogenated to hydroxyl groups under high pressure and temperature (4-12 MPa, 403–423 K) [19]. Sugar alcohols are non-cariogenic: they add sweetness with low-calorie properties and a cooling effect to their wide range of industrial applications. They have applications in the food and pharmaceutical fields, besides their characteristic platform molecule characteristic ability to be employed as feedstock for synthesizing several value-added chemicals. The most interesting sugar alcohols emerging from biomass production processes are sorbitol, erythritol, mannitol and xylitol. Xylitol and sorbitol are commonly used in pharma and food companies, personal care products and as a precursor for value-added derivatives. Alditol sugars such as sorbitol, xylitol, and mannitol can be synthesized via catalytic hydrogenation of the corresponding aldoses or ketoses employing solid

catalysts, e. g. nickel catalysts. An alternative is through biochemical pathways using *E. coli* as an effective host organism.

Sorbitol is a six-carbon sugar alcohol with six hydroxyl groups. It shows high solubility in water and low sweetness. Its chemical structure gives sorbitol a high versatility for a various range of applications in the food and chemical industries. The pharmaceutical, cosmetic and textile industries utilize it as drug delivery system and humectant. Sorbitol can be further synthesized into other value-added chemicals, such as sorbitan, glycol, glycerol, and lactic acid. It can also be converted to light alkanes via aqueous phase reforming with Pt/Al_2O_3 catalyst as Huber and Dumesic reported. [19] Various pathways have been reported to produce sorbitol. Sorbitol can also be obtained through catalytic conversion of several polysaccharides (especially starch) via hydrogenolysis typically on Ni. Recent work [19] has reported high conversions of glucose (95%) to yield 84 wt% sorbitol using a mesoporous Ni/NiO catalyst, which is associated with the acid side density of the catalyst, its high surface area and high acid site availability with low deactivation degree in reusabilitytests.

Xylitol is a C_5-sugar alcohol obtained only from biomass-based pentoses, since it has no petrochemical alternative. This sugar alcohol is broadly used in the food, odontological, and pharmaceutical industries due to the characteristic advantages of polyalcohols. Furthermore, it has been employed to prevent acute otitis in small children and to replace sugar in food and beverages for people with diabetes due to its comparable sweetness to sucrose. Xylitol is industrially manufactured by catalytic hydrogenation of xylose. In the Figure 19 is presented a catalytic hydrogenation over Ni-Re bimetallic nanoparticle catalyst, whose yield is up to 98% [24].

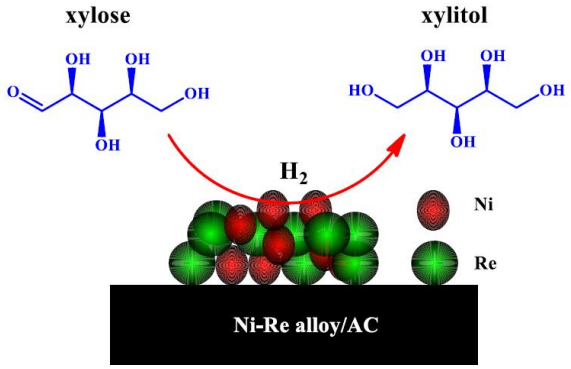


Figure 19. Catalytic hydrogenation over Ni-Re bimetallic nanoparticle catalyst [24]

Even though biotechnological advances have been studied to replace the chemical process, it is not yet possible at large scale. The catalytic conversion of xylose into xylitol is associated with the presence of a metallic catalyst (typically Raney nickel) at high temperatures (373–418 K) and elevated pressure conditions up to 5066 kPa. Xylitol can also be microbial produced from glucose and

cellobiose. Nevertheless, several biochemical reductions have also been reported. Xylitol can also be synthesized with a ruthenium-based catalyst under extreme operating conditions (referencce platform molecules) which increase the production cost and market price of xylitol. Contrastingly, biotechnical production is increasing in importance because it offers an alternative without extreme operating conditions. The most promising organisms are *Saccharomyces cerevisiae* and various *Candida* yeasts.

3. Production of amino acids from biomass

3.1. Amino acids and their importance

Amino acids are the building blocks of proteins and the primary source of nitrogen for tissues in the human body – they serve as precursors for other nitrogen compounds [25]. Because of this and their numerous applications, in present, amino acids are widely produced and used in many fields.

The world annual production of amino acids amounted to about 6.5 million tons in 2014. Moreover, the market volume is still expected to grow at a rate of about 6-8% per year [26]. Each amino acid molecule presents an amino group ($-NH_2$) and a carboxyl group (-COOH) and for this they are known as amphoteric molecules. One of the important properties of these molecules is their reactivity. Amino acids express novel functions by reacting with other substances. For instance, the glutamate amino acid can react with fatty acids producing N-acyl glutamate, a substance which is known for her detergent activity. Because of this the product is used in the cosmetics field as a nonirritating soap. Due to the particular structure they have, amino acids can form proteins by connecting the amino group of an amino acid molecule to the carboxylic group of another amino acid. Our bodies contains hundreds of thousands of proteins [reference 1a] and it is estimated that the number of types of proteins from the whole world is around 10^{10}-10^{12} [25].

Proteins are the building blocks of our body: hair, skin, muscles, bones, tissues and internal organs. They also perform other important functions such as providing nutrition (by breaking up to amino acid, followed by absorption and chemical transformation in other nutrients), protecting the body (through the immune system) and controlling metabolic reactions [27]. Proteins make up approximately 20% of the human body. Although there are over 100.000 types of proteins, they are made up of only 20 types of amino acids. So, the conclusions that can be drawn are that amino acids are the essence of life and they have a tremendous importance. For instance, amino acids are crucial to the taste of food. They interact with other ingredients present in food, to create the final taste. Each

amino acids has its own taste: glutamic acid taste like umami, glycine, lanine, proline are sweet, tyrosine, leucine are bitter and so on.

Another important field in which amino acids are essential is the livestock industry: using amino acids as feedstock for animals we can obtain better result in terms of speeding their growth. In the field of pharmaceuticals amino acids are extremely valuable. With the use of this we can feed patients which suffer for poor nutrition or diseases that affect the digestive system, such as decompensated cirrhosis and hepatitis. For example, in patients with liver cirrhosis a significant decrease in BCAA (branched-chain amino acid such as valine, leucine, isoleucine) levels in the plasma may lead to malnutrition or severe hepatic encephalopathy. It was found that supplementation of BCAA will improve the nutritional status and lengthened patient survival time [28].

Recently, amino acids have attracted more attention in the cosmetics market. The estimated market of amino acids for use in cosmetics was 14.000 tons per year, in 2012. Amino acids are also used for skincare. A diet rich in proteins with good amino acid balance is effective to maintain beautiful skin. Likewise, amino acids play a role in protecting hair from further damage, replenishing the voids created by the loss of proteins and moisturizing the hair [27].

In the nutritional field the 20 amino acids are divided into two categories: essential (indispensable) amino acids and nonessential (dispensable) amino acids. Essential amino acids are not produced by our body and therefore must be obtained through food. Such amino acids are: valine, leucine, isoleucine, methionine, threonine, phenylalanine, tryptophan and histidine. It is often assumed that only essential amino acids are important, whereas nonessential amino acids are not so important. However, this assumption has recently been proven to be wrong. Nonessential amino acids have many biological functions, not only as building blocks but also as intermediates in the metabolic system of the body [27]. Because of this we should pay more attention to the synthesis of these amino acids. In recent years, many fundamental food and biotechnology businesses are being developed on the basis of the newly discovered physiological functions of amino acids.

3. 2. Obtaining amino acids by known processes

Amino acids are valuable products for industry due to their versatility. Nowadays, glutamic acid, lysine, methionine and threonine cover more than 95% of the total market volume [26]. This is why the researchers focus now in developing on two directions: the discovery of new production

methods regarding this four amino acids and the discovery of production methods regarding the rest of amino acids.

The literature for the use and transformation of amino acids is extremely diverse. In general, however, these focus on use of amino acids in nutrition, medicine, impact on physiological function, along with their use as platform molecules. In particular, they promote health by several actions, including reduction of the adiposity, regulation of the muscle protein metabolism and the control of the growth and immunity of the organism. Also, it is well documented that an amino acids deficiency causes serious diseases, both in humans and animals [29]. Therefore, the interest in investigating and developing new routes to produce them in a more cost-effective and sustainable way has significantly increased in the last years.

In present, amino acids are produced through three different routes: microbial processes (fermentation and enzymatic synthesis), chemical synthesis and extraction from protein-hydrolysates. As a short history of the production of amino acids it must say that the first researcher who started the experiments with the aim of identifying and purifying the flavour enhancing principle from the seaweed konbu was Kikunae Ikeda in 1907 at the Tokio Imperial University [29]. After a year of research he discovered that the extract consisted of monosodium glutamate (MSG) and for this it is considered the father of MSG as he provided the bases for the amino acid production industry. However, the industrial processes to produce amino acids still need to be optimized.

The first route to produce amino acids is through biological processes such as fermentation and enzymatically catalyzed synthesis. Most of the current industrial processes for amino acids production are based on fermentation route so we will focus on this. In this process, under aerobic or anaerobic conditions, several microorganism are used in order to convert the sugars present in a substrate into a broad spectrum of amino acids [13]. The discovery of the soil bacterium, *Corynebacterium glutamicum*, which is capable of producing L-glutamic acid with high productivity from sugar, paved the way for the success of the fermentation technique in amino acid production. Generally, the fermentation takes place in an aqueous medium containing essential nutrients such as sources of carbon, nitrogen, phosphorus and sulfur, vitamins and minerals. Identifying a suitable carbon source is a major challenge, because it should not only serve as an energy source for the microorganism, but also as a precursor for the structural skeleton of the amino acid metabolite [26]. The fermentation process is in principle very simple, involving the following three steps: first, a fermentation tank is charged under sterile conditions with a culture medium containing a suitable carbon source, such as sugar cane syrup, as well as the required nitrogen, sulfur and phosphorus sources and some trace elements. The second

step involves adding of a culture from the production strain prepared in a prefermenter to the fermentation tank and stirring under specified conditions (temperature, pH, aeration). The L-glutamic acid released by the microorganism into the fermentation solution is then obtained by crystallization in the recover section of the fermentation plant, in the third step [30]. In case of other amino acids production, which cannot be separated so easily from fermentation broth, other separation techniques such centrifugation or filtration can be used, followed by a purification step using chromatographic techniques chosen according to the product properties such as solubility, isoelectric point and affinity to adsorbent [29]. Fermentation has several advantages compared to the other methods. First of all, it produces only the L-form amino acids, avoiding further purification steps. Another important factor is that it can be operated at mild conditions preventing product degradation. Furthermore, the maintenance costs are significantly lower compared to the extraction processes. On the other hand, fermentation requires sterility and high energy consumption for oxygen transfer (for the aerobic fermentations) and mixing as well as water addition. All of this have a huge impact on capital and operation costs. Moreover, requirement of bigger reactors, compared to the other amino acids production methods, leads to a high capital investment [29].

The most common bacteria used for amino acid production via fermentation are *C. glutamicum* and *E.Coli*. Both can produce a wide range of amino acids. Using *C. glutamicum* we can produce several amino acids such as: L-glutamate, L-lysine, L-phenylalanine, L-threonine, L-tryptofan. If *E.Coli* is used instead L-methionine, L-lysine, L-threonine can be produced. Moreover, metabolic engineering techniques can enable the creation of a mutant strain of *E.Coli*, able to produce the branched chain amino acids L-valine, L-leucine and L-isoleucine, which are extremely interesting for their potential as feed additives, cosmetics and pharmaceuticals.

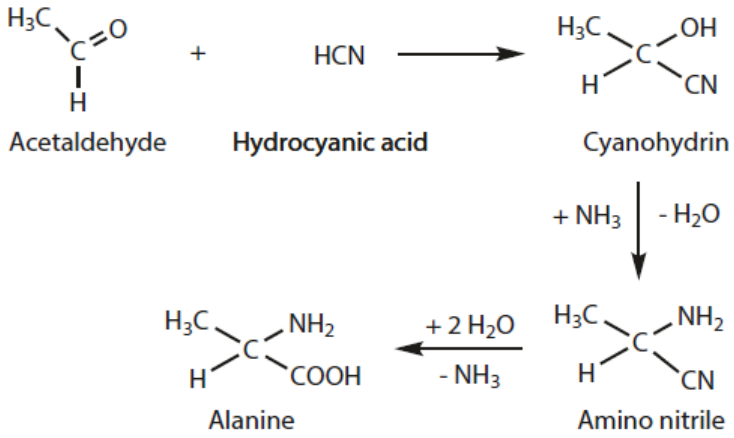
The second biological process in the production of amino acids is the enzymatic one or the enzymatic conversion. The enzymatic process is based on the action of an enzyme or a combination of enzymes to catalyze the production of the desired amino acids [29]. For instance, aspartic acid is obtained by the addition of ammonia to fumarate the reaction being catalyzed by the enzyme aspartate ammonialyase [26]. Moreover, alanine can be produced by a consecutive decarboxylation of aspartic acid mediated by aspartate β-decarboxylase. A key factor for the successful development of biocatalytic processes is the possibility to employ on a large-scale an inexpensive enzyme with suitable properties (i.e. high activity, stability and selectivity) [31]. Several enzymes have been used such as hydrolytic enzymes, ammonia lyases, NAD^+-dependent L-amino acid dehydrogenases. Most of these

enzymes are obtained from microorganism such as *E.Coli, Saccharomyces cerevisiae, Pseudomonas dacunhae* and *Cryptococcus lurendii* [29].

In the same time, the amino acid industry and in special the pharmaceutical one, wants amino acids optically pure. The enzymatic process fulfils this condition so the main advantage is that it can produce optically pure D and L-amino acids, in higher concentrations and with a very low by-products formation, which is in alignment with the principles of green chemistry. On the other hand, the enzymes are usually expensive and their stability is one of the main drawbacks of this process. Therefore, various techniques based on immobilized biocatalysts have been developed in order to improve the performance of the process. However, this is not the best method to produce L-amino acids at industrial scale [29].

Historically, chemical synthesis has been the classical pathway to produce achiral amino acids like glycine or a racemic mixture of D,L-methionine or D,L-alanine [29]. In present, when we talk about chemical synthesis we refer to the Strecker synthesis (production of methionine), the Gabriel malonic ester synthesis (when we obtain as secondary product) and the Miller synthesis [32] (which aims to obtain amino acids by reproducing the primitive conditions when organic compounds were formed in an atmosphere rich in methane, ammonia, water and hydrogen).

The first amino acid synthesis was reported in 1850 with the name of Strecker synthesis. According to this reaction the conversion of an aldehyde or ketone and amine or ammonia to α-amino acids can be achieved by means of an acid catalysts, metal cyanide and water as shown in Scheme 7.

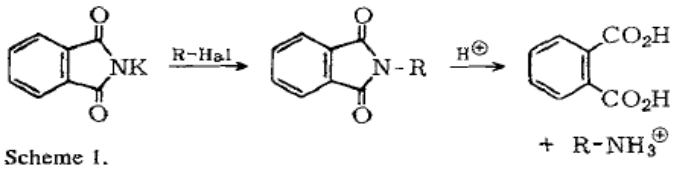


Scheme 7. Strecker's synthesis [33]

The Strecker synthesis of amino acids has been considered as one of the modes of formation of amino acids in the primordial Earth [33]. In particular it consists in the reaction of an aldehyde with hydrogen cyanide and D-α-methylbenzylamine in methanol, followed by the hydrolysis of the resulting amino nitrile to yield the N-α-methylbenzyl amino acid. Finally, a catalytic hydrogenolysis is performed to remove the metylbenzyl group from the amino acid molecule [29]. The main drawbacks of the chemical synthesis are associated to the price of the catalyst as well as to the use of hazardous cyanide sources. To overcome these problems new methods were developed, starting from the catalytic asymmetric Strecker-type reaction introduced in 1963 by K. Harada [33].

The most common industrial chemical process for the manufacture of racemic amino acids is the so-called Bucherer-Bergs method [34] which is a variant for the Strecker synthesis This method proceeds via a hydantoin intermediate that is generated from an aldehyde, hydrogen cyanide and an ammonium salt. However, this approach is far less attractive than fermentation or enzymathic catalysis because an expensive optical resolution step is required to isolate the bio-active L-isomer from the amino acid racemate [26]. This approach is therefore involved only in the production of achiral glycine and D,L-methionine, since the adults and animals are able to convert D-methionine to the L-isomer by transamination. Although the Bucherer-Bergs approach is the most common because of its simplicity and effectiveness, the main drawbacks of this method are the long time reactions time and the elevated temperature.

Another method of producing amino acids, developed in time is the Gabriel malonic ester synthesis. The reaction takes place in two steps as shown in the Scheme 8.



Scheme 1.

Scheme 8. Gabriel's synthesis[35]

In the first step potassium phtalimide reacts with halogenoalkanes and with a variety of other alkylating agents and leads to the N-alkylphtalimide. Furhermore, the N-substituted phtlamides may be converted into the corresponding primary amine by hydrolysis or hydrazinolysis [35]. The importance of the Gabriel synthesis lies in the absence of secondary or tertiary amine contamination of the primary amine and the toleration of a very wide range of other functional groups in the molecule. In the same time, the mild conditions are now available for accomplishing both stages so there is hope.

The last production method of amino acids is the Miller`s synthesis which is based on the idea that organic compounds that serve as the basis of life were formed when the earth had an atmosphere of methane, ammonia, water and hydrogen, instead of carbon dioxide, nitrogen, oxygen and water [32]. In order to test this Miller built an apparatus which circulated CH_4, NH_3, H_2O and H_2, past an electric charge. Electrical discharge, according to Miller, may have played a significant role in the formation of compounds in the primitive atmosphere. The apparatus used by Miller is presented in Figure 20.

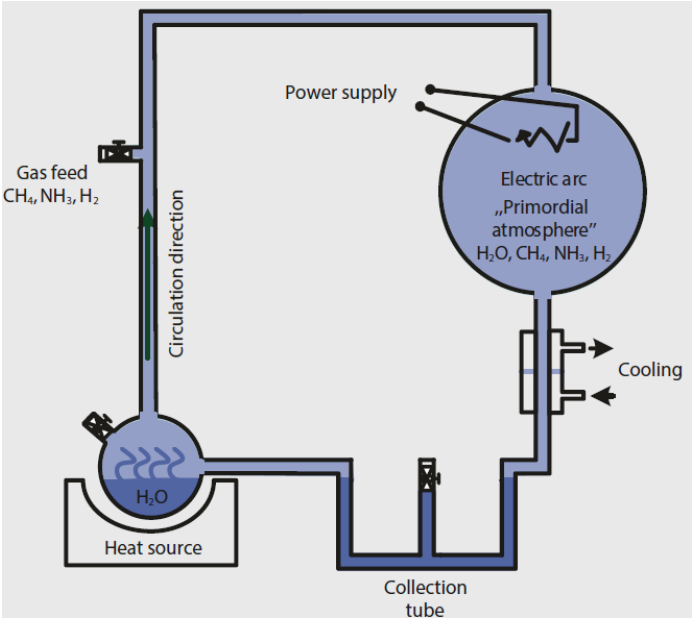


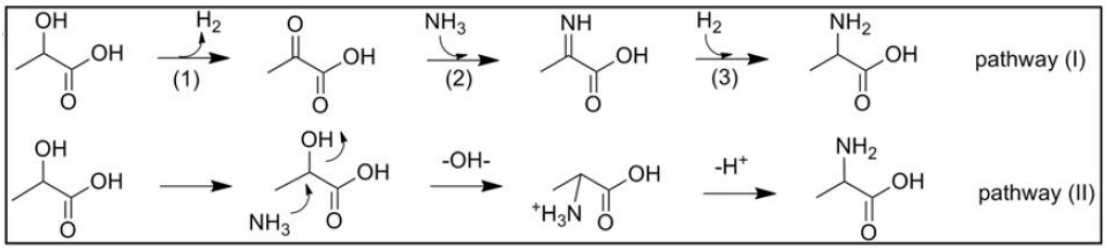
Figure 20. The apparatus used in Miller's synthesis [32]

Water is boiled in the flask and it is mixed with the gases in the 5 litters flask. Then, the water circulates past the electrodes, condenses and empties back into the boiling flask. The U-tube is used because it prevents circulation in the opposite direction. The acids and amino acids formed in the discharge, not being volatile, accumulate in the water phase. In the condensed water phase, various organic molecules were detected at the end of the experiment, including larger amounts of the proteinogenic amino acids glycine and alanine. It is regarded to be certain that these were formed by Strecker synthesis with the intermediate products hydrocyanic acid, formaldehyde and acetaldehyde respectively [36]. Then the resulting mixture is tested using paper chromatography to see if amino acids were obtained.

The last method used in producing amino acids is based on extraction. This method exploits, in order to separate the amino acids, the differences in their physicochemical properties such as chemical affinity and pH. Extraction from protein-hydrolysates is suitable for large scale industrial production

but only for a few amino acids such as L-cysteine, L-leucine and L-tyrosine. So, according to the amino acids of interest, different extraction processes are or can be developed [29]. For instance, if we talk about L-cysteine, this is traditionally produced from keratin contained in animal and human material such as feathers, bristles and hair, using activated charcoal and concentrated hydrochloric acid. So, regarding this method, the main advantage relies in the use of industrial by-products or wastes. Some more advantages are: the simplicity of the method applied, the accessibility of the reagents used and the well established process. More effective extraction methods are the one that utilize water at subcritical (100°C<T<374.2°C) or supercritical (T=374.2 K and P=22.05 Pa) conditions [29]. Such a method was described in 2008 by Sereewatthanawut et al. [37] when they tested the effect of different temperature and hydrolyses time in a subcritical water process. The result demonstrated that the amino acids yield increases with temperature and time. In particular, a higher temperature is associated with an increasing in the dissociation constant of water (K_w) and thus the concentration of hydronium and hydroxide ions increases. Other examples are L-leucine, L-alanine and L-serine which are produced from proteinaceous biomass waste material derived from animals [29]. These amino acids are extracted in subcritical water, with temperatures ranging from 180 to 320°C and pressures from 3 to 30 MPa. These study demonstrated that hydrolyses reaction time and temperature are very important to obtain high yield of amino acids. Moreover, the subcritical and supercritical methods, utilized to decompose organic matter into smaller molecules, are environmentally friendly. Because of this is very possible that in the future they will be used more and more.

In present are many attempts to transform α-keto acids and α-hydroxy acids into α-amino acids. This is because amino acids are the building blocks for protein biosynthesis, finding uses in a myriad of industrial applications. We can obtain α-keto acids and α-hydroxy acids from biomass i.e. lignocelullose and after that convert them into amino acids or directly from biomass. To that end, W.Deng et al. [38] reported a heterogeneous catalysts that directly transforms lignocellulose biomass-derived α-hydroxy acids into α-amino acids, including alanine, leucine, valine, aspartic acid and phenylalanine in high yields. The reaction mechanism is presented in the Scheme 9.



Scheme 9. Two possible reaction pathways for amination of lactic acid to alanine [38]

The catalyst used was ruthenium nanoparticles supported on carbon nanotubes (Ru/CNT) which exhibits exceptional efficiency compared with catalyst based on other metals. This happens due to the unique, reversible enhancement effect of NH_3 on Ru in dehydrogenation. Based on the catalytic system, a two-step chemical process was designed to convert glucose to alanine in 43% yield, comparable with the well-established microbial cultivation process presented above. The present strategy enables a route for the production of amino acids from renewable feedstocks. They used Ru due to his unique performance, which can be explained in three ways. First, the in situ formed α-keto acid could only be effectively converted to the amino acid by the Ru catalyst. Second, alanine decomposes over other metal catalysts under the reaction conditions. Third, the ability of other metal catalysts to perform the dehydrogenation step is suppressed in the presence of other reagents such as NH_3, whereas in this case was maintained or even enhanced by the Ru/CNT catalyst.

Another pathway of obtaining amino acids (in special alanine) from waste glycerol was proposed by Y.Wang et al.[10] They reported a one-step protocol to covert crude glycerol from the biodiesel industry into 43% yield alanine over a Ru_1Ni_7/MgO catalyst. The multifunctional catalytic system promotes glycerol conversion into lactic acid, and then to alanine,, as shown in Figure 21.

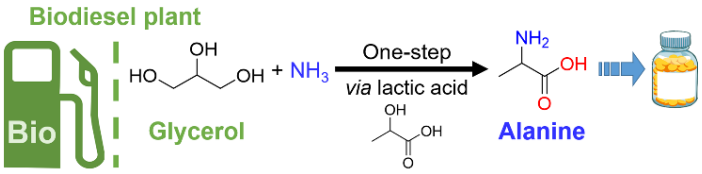


Figure 21. An illustration of one-step conversion of waste glycerol to alanine [10]

They concluded, after performing X-ray absorption spectroscopy and scanning transmission electron microscopy, that exists bimetallic RuNi species and Ni-doped Ru substantially decreases the E_a of C-H bond dissociation of lactate alkoxide to form pyruvate, which is the rate determining step. A plausible explanation for this behavior is that the unreacted glycerol inhibit lactic acid and amination reaction.

An attempt of converting biomass to amino acids was made in 2020 by S. Song et al. [39] when they identify that CdS nanosheets are an efficient and stable catalyst, exhibiting an higher activity in production of alanine from lactic acid, compared to commercial CdS as well a CdS nanoobjects bearing other morphologies. The occuring reaction, presented in Figure 22 is a photocatalytic one, CdS representing the only material able to promote the desired transformation under visible light.

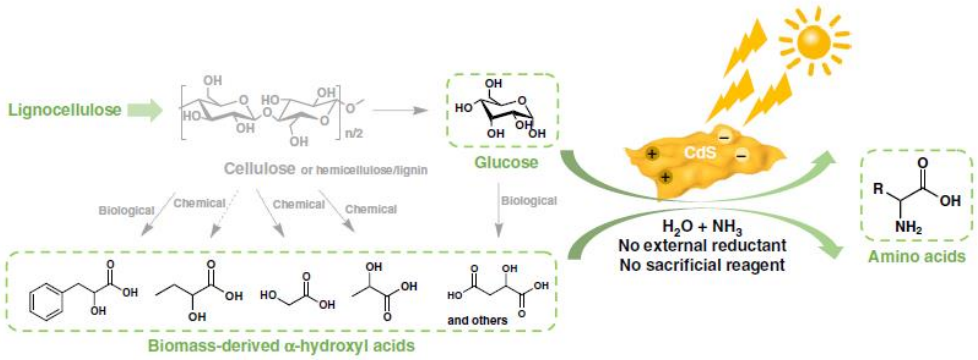


Figure 22. Photocatalytic amination of glucose or biomass-derived α-hydroxyl acids to amino acids[39]

The unique properties of CdS nanosheets are attributed mainly to the preferential formation of oxygen-centered radicals to promote α-hydroxyl acids conversion to α-keto acids and partially to the poor H_2 evolution which is an undesired reaction. Encouragingly, a number of amino acids were prepared using the proposed protocol, with high yields, and one-pot conversion of glucose to alanine was also achieved, under mild conditions.

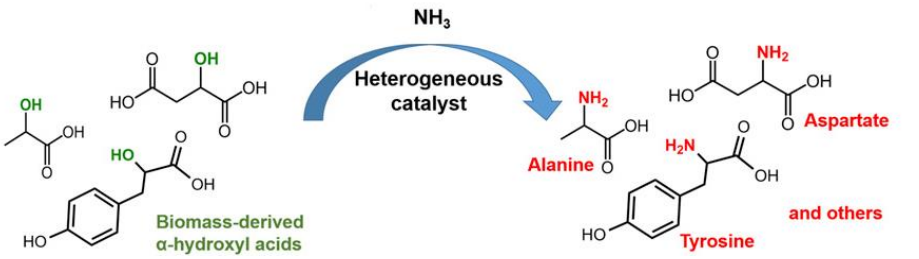
T.Fukushima and M. Yamauchi [40] made another attempt to transform biomass into amino acids using titanium dioxide by electrochemical synthesis. They reported that seven amino acids were electrochemically synthesized from biomass-derivable α-ket acids and NH_2OH with faradaic efficiencies (FEs) of 77-99%, using an earth-abundant TiO_2 catalysts.

4. Summary

- The discovery and investigation of novel and efficient pathways for the conversion of biomass into chemicals are among the big challenges facing heterogeneous catalysis of our days.
- The specific properties of biomass pose new requirements on the processes and on the solids that have to be used as catalysts for its conversion.
- Due to the importance of lignocellulosic materials a special attention is given on the desired properties of solid catalysts for its efficiently conversion.
- Amino acids are the building blocks for protein biosynthesis and find use in myriad industrial applications including in food for humans, in animal feed, and as precursors for bio-based plastics, among others.
- Today, amino acids are primarily manufactured via microbial cultivation processes, which are costly, are time consuming, and require extensive separations processes.
- The development of efficient chemical methods to convert abundant and renewable feedstocks into amino acids has been largely unsuccessful to date.
- As an alternative, chemocatalytic approaches to produce amino acids from renewable feedstocks such as bio-based sugars could offer a rapid and potentially more efficient means of amino acid synthesis.

5. Perspectives

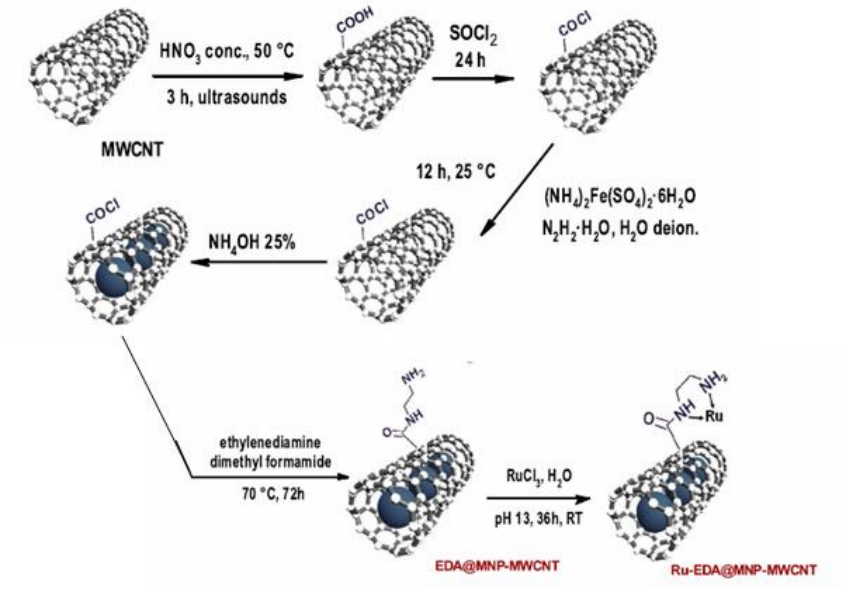
Based on the literature investigation, the aim of the further research is to develop an efficient heterogeneous catalyst able to directly transform lignocellulosic biomass-derived α-hydroxyl acids into α-amino acids, including alanine, leucine, valine, aspartic acid, and phenylalanine in high yields. To date, sustainable and generalizable approaches for the direct synthesis of amino acids from abundant and renewable feedstocks using NH_3 are still quite rare.



Schematic illustration of α-hydroxyl acids transformation into α-amino acids through ammination and in the presence of a solid catalyst

For this a series of Ru@MNP-MWCNT catalysts will be synthesized via functionalization of nanostructured carbon-based carriers (i.e. MWCNT) with ethylenediamine followed by the complexation with $RuCl_3$.

To ensure an easy recovery and high recyclability the MWCNTs nanotubes will be modified by incorporation of super-paramagnetic Fe_3O_4 nanoparticles into porous structure.



Schematic representation of the Ru@MNP-MWCNT catalysts

Why Ru@MNP-MWCNT? Literature study indicates that ruthenium nanoparticles supported on carbon nanotubes (Ru/CNT) exhibit exceptional efficiency compared with catalysts based on other metals, due to the unique, reversible enhancement effect of NH3 on Ru in dehydrogenation.

The activity of some Ru complexes for hydrogenation is remarkably enhanced with the addition of one equivalent of diamine because the ligand and the Ru metal work cooperatively to activate substrates.

Why magnetic nanoparticles? To overcome the catalysts separation issue, the use of magnetic nanoparticles emerge as a viable solution; their insoluble and paramagnetic nature enables their easy and efficient separation from the reaction mixture with an external magnet.

By creating *Ru@MNP-MWCNT* systems we have the reason to believe we will create an efficient heterogeneous catalyst for α-amino acids synthesis, not only with a high activity and selectivity (like a homogeneous one) but also easily to separate and recycling (like a heterogeneous one).

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