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Production of Bio-methane Gas as Renewable Energy Source - A Review

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Abstract: The present review aims to provide an up-to-date summary of bio-methane (CH_4) gas production, which use as is a renewable energy source. Burned bio-methane gas used for water heating, space heating, drying, or cooking. CH_4 is also used in an automotive to produce both heat and electricity. The bio-methane gas is produced by anaerobic digestion (AD) technology of food waste, agricultural waste, municipal waste, green waste, manure, and sewage. AD technolog is promising technology; having the potential to convert several bio-masses into bio-gas rich with methane gas, which is alternative to fossil fuels. The hydrolysis, acidogenesis, acetogenesis, and methanogenesis are essential steps of AD process. The steps are proceeding by different kind of bacteria such as, acidogenic, acetogenic, and methanogenic bacteria. An effective process to increase the productivity of an anaerobic digestion process by combining it with a microbial electrosynthesis system (MES) was developed. Percentage compositions of CH_4 from anaerobic digestion of a different feedstock were between 50% - 84%. The various physical, chemical, physiochemical and, biological pretreatments methods were applied to break the complex biomass into easily digested components. The AD system has many advantages, like low energy consumption, low nutrient and chemical requirement, improved sanitation, pathogens reduction, reduction of disease transmission, greenhouse emissions and nitrous oxide emissions reduction, etc. And some of the anaerobic digestion disadvantages are a long start-up, high buffer requirements for pH controlling, higher sensitivity of microorganisms to pH and temperature, etc. More advantages and disadvantages are discussed in this review. In the future, will be solutions to problems that limits production yield.

Keywords: Bio-methane Gas, Renewable Energy, Anaerobic Digestion, Biomass

1. Introduction

Methane gas made up of one carbon atom and four hydrogen atoms. It's lighter than air, odorless, highly flammable, occurs naturally as a component of natural gas. The generation of bio-methane from biomass is one of the renewable energy sources. Production of bio-methane gas by anaerobic metabolism yields a clean fuel from renewable feedstock to replace the energy produced by fossil fuel. This reduces environmental effects regarding acid rain and global warming [1].

Bio-methane is using for replacing fossil fuels in heat, power generation, and vehicle fuel. Dry and wet fermentation systems are using for biogas production [2]. Because of the environmental impact of classical energy source (remarkably crude oil), and variable costs there is an increasing interest in renewable energy using. Renewable energy gradually becomes important because of the negative environmental effects of greenhouse gas (GHG) emissions. As known that common sources have a lifetime and totally will be consumed in the future, so another goal for using renewable energy sources is the issue of sustainability. The biogas production process is noncomplex, and the transformation of organic sources into biogas is approximately 5-10wt. %, according to the type of nutrient and the condition of the procedure. The biogas is a product of anaerobic digestion (AD), where several microorganisms break down organic material within various metabolic methods. Biomasses are a common renewable energy source as well as other sources (wind, hydro, solar, geothermal) [3]. Methane (CH_4) gas formed using biodegradable substances such as agriculture residues, wastewater, vegetable wastes, cattle manure, and human excreta [4, 5]. Anaerobic digestion (AD) meaning is that the bacterial breakdown of organic substances in the lack of oxygen. Anaerobic digestion gives important benefits over aerobic operations, like low energy loss, a decrease of solids production, low nutrient demand and, potential energy recapture from the bio-methane created [6]. This method is now broadly used in many environmental applications, in diverse forms, and method of action. Most biogas generation is from sewage sludge. In the future high amount of biogas (about 224 TW.h) will be created by using wet manure, undigested sewage sludge, landfill, and food-processing residues [7].

2. Feedstock's for Bio-methane Gas Production

The main categories are organic waste like food waste, a fraction of municipal solid waste, and agricultural waste.

2.1. Types of Biomass for Gas Production

All types of biomass can be used as matter for biogas creation if they contain fats, proteins, carbohydrates, cellulose, and hemicelluloses as main ingredients. Food wastes are rich in organic soluble that are turned into volatile fatty acids. Organic fractions of municipal solid waste contain food waste (fruit peels or vegetables) and yard waste (grasses or leaves). And Agricultural residues are good raw material, for anaerobic digestion in the case of the solid-state, due to their effluent feeding, low costs and, high possibility of biogas production. The cellulosic and hemicellulosic carbohydrates are not helpful for rapid fermentation [8].

2.2. Biomass with High Methane Yield

The gas yield differs with the content of proteins, carbohydrates, and fats [2]. There are many organic substances for high methane yield. The organic municipal solid waste, fruit waste, vegetable waste, leaf, grassy, woody, weed biomass, marine biomass and, freshwater biomasses are sustainable for high methane gas production. Table 1 illustrates biomasses with high methane productivity in m^3/kg volatile solids (VS) [3].

Table 1. *Biomass with high CH_4 productivity.*

Type of biomass	Methane yield (m^3/kg VS)
Organic municipal solid waste	0.390-0.403
Fruit, vegetable and, leaf	
The fruit and the stem of banana	0.529
Potato waste	0.426
The waste from processing of tomato	0.420
Waste of carrot	0.417
Peeling of banana	0.409±0.002
Grassy biomass	
Sorghum	0.420
Milet straw	0.390
Wheat straw	0.383
Paddy straw	0.367
Corn stover	0.360
Woody biomass	
Iponnoea stem	0.426
Wood of poplar	0.330
Pre-treated vine shoot	0.315
Weed	
Partially decomposed Ageratum	0.241
Lantana (treated with sodium hydroxide) + cow manure	0.236
Parthenium (treated with sodium hydroxide)	0.236
Marine	
Ulea and *Chaetomarpha*	0.480
Ulea	0.330
Maerocystis pyrifera	0.310
Freshwater biomass	
Pisitia	0.410
Water hyacinth treated with NaOH	0.362

VS=volatile solid

3. Bio-methane Production

The methane gas concentration in the troposphere is 1.8 ppm. It is one of the extreme greenhouse gas following H_2O vapor and CO_2 [9]. Bio-methane is a renewable energy source generated by the anaerobic metabolism of organic matter, which is rich in methane gas and liquid effluent. [10]. So with controlling the use of organic wastes that lead to the generation of environmentally polluting gases, it's easy to control the spontaneous emission of greenhouse gases in all sources, particularly landfills. Biogas consists about 55% - 80% and 20% - 45% methane and carbon dioxide respectively [10]. During methane production, a small quantity of ammonia (NH_3), water vapor (H_2O) and, hydrogen sulfide (H_2S) maybe create. The digested effluent generated during bio-methane gas production can be later used without further treatment to the land as fertilizer or separated from the solids and used as a liquid fertilizer [10].

3.1. Chemistry of Anaerobic Digestion

The AD method has four stages, which vary from each other in their specific group of microorganisms. The four stages, namely, hydrolysis, acetogenesis, methanogenesis, and acidogenesis [2, 10-13]. The breakdown of feedstock under anaerobic conditions is promoted by a mixture of microorganisms existing in every step leading to the formation mixture of gases in which the CH_4 gas is the principal constituent [10, 12].

The reactions steps of the anaerobic digestion procedure are illustrated in figure 1.

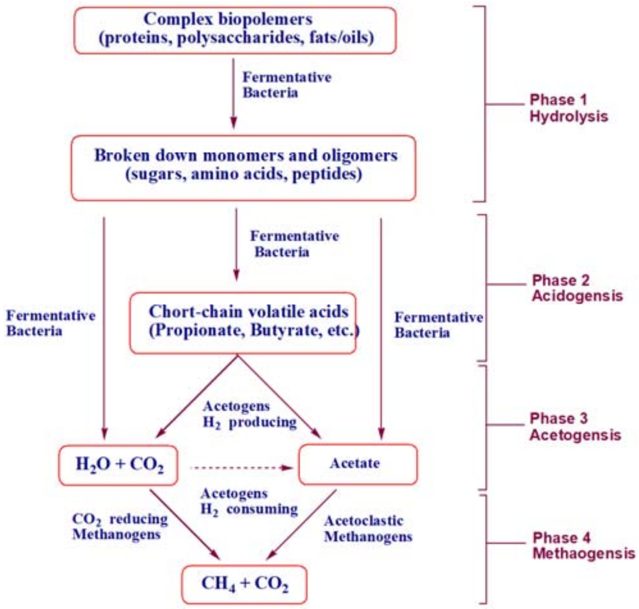

Figure 1. *Bio-methane production by anaerobic digestion reactions.*

3.1.1. Hydrolysis

Hydrolysis is considered as the cleavage of the chemical bonds by water. Ions react with the water molecules by adjusting the pH to generate an H-O bond cleavage. Hydrolysis is first step, occurs to convert complex organic polymers to simple and soluble molecules. The proteins hydrolyzed to amino acids; lipids hydrolyzed to long-chain fatty acids and, the carbohydrate hydrolyzed to sugars [8, 12, 14]. The hydrolysis step is a moderately slow step if solid waste is used. So the rate of the overall digestion process can limit. Equation (1) describes hydrolysis reaction [15].

$$(C_6H_{10}O_5)n + n\ H_2O \rightarrow n\ C_6H_{12}O_6 + nH_2 \quad (1)$$

$C_6H_{10}O_5$ (cellulose) hydrolyzed by H_2O (water) to give $C_6H_{12}O_6$ (glucose) and H_2 (hydrogen gas). For this reaction to occur, it requires catalysts, either homogenous or heterogeneous acids.

The reaction represents in equation (1) is the breaking of the linkages β-1, 4-glycosidic, which is the fundamental step that can introduce the catalysis into the reaction step. The two ions involved in this reaction are the hydrogen ion and hydroxide ion. The two ions are the products of water dissociation however; they can react with cellulose molecules to produce many products later [15].

3.1.2. Acidogenesis

The Acidogenesis stage is a fermentation process. During this process, the soluble compounds produced by a hydrolysis process, are degraded and converted into carbon dioxide and hydrogen gas through specific fermentative bacteria (acidogenic bacteria). Acetic acid uses in the fermentation step as a substrate by CH_4-creating bacteria. The acidogenesis reactions occur as represented in equations (2)-(4).

$$C_6H_{12}O_6 \leftrightarrow 2\ CO_2 + 2\ CH_3CH_2OH \quad (2)$$

$$2\ H_2 + C_6H_{12}O_6 \leftrightarrow 2\ CH_3CH_2COOH + 2\ H_2O \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

Usually, it is hard to distinguish between acidogenic and acetogenic reactions. The two reactions produce hydrogen gas and acetate. The two products are components for methanogenic bacteria in the methanogenesis stage [15].

3.1.3. Acetogenesis

Hydrogen gas is the waste product of the acetogenesis process. So the stage is called the dehydrogenation step. There is inhibition of the metabolism of acetogenic bacteria by the hydrogen gas. Hydrogen gas can inhibit this stage if not consumed by hydrogen formation bacteria. Equations (5)-(7) represent the reaction set related to this phase of the anaerobic digestion process.

$$3\ H_2O + CH_3CH_2COO^- \leftrightarrow 3\ H_2 + H^+HCO_3^- + CH_3COO^- \quad (5)$$

$$2\ H_2O + C_6H_{12}O_6 \leftrightarrow 4\ H_2 + 2\ CH_3COOH + 2\ CO_2 \quad (6)$$

$$2\ H_2O + CH_3CH_2OH \leftrightarrow 3H_2 + H^+ + CH_3COO^- \quad (7)$$

According to equation (5), the acidic phase products turn to hydrogen gas and acetate ion. The two products can be used in the following methanogenesis phase. Some bacteria like *Methanobacterium propionicum* and. *Methanobacterium suboxydans* decompose the product of the acid phase into the acetate.

Biogas production efficiency can be explained through the stage of AD acetogenesis. About 70% of CH_4 is produced via the reduction of acetate CH_3COO^- as principal product during the process of the digestion; while 25% of acetate and approximately 11% of hydrogen gas are produced in this step [15].

3.1.4. Methanogenesis

This stage involves two steps of the AD process; the fourth and final stages. Mainly, methanogens bacteria convert acetic acid and hydrogen gas into carbon dioxide gas and methane gas. Methanogens bacteria cannot grow in oxygen atmosphere. Equation (8-10) explains the processes of methanogenic stage of AD processes.

$$CH_3COOH \rightarrow CO_2 + CH_4 \quad (8)$$

$$4\ H_2 + CO_2 \rightarrow 2\ H_2O + CH_4 \quad (9)$$

$$CO_2 + 2\ CH_3CH_2OH \rightarrow 2\ CH_3COOH + CH_4 \quad (10)$$

Equation (8) shows the dissociation of acetic acid into methane and carbon dioxide. In equation (9), carbon dioxide is reduced to methane via hydrogen gas. Finally, in Equation (10), methane gas is produced by the decarboxylation of ethanol [15]. It appears that there are six main tracks in the process of the methanogenesis stage. In every track, there are different substrates converted into methane gas. Acetic acid, methanol, formic acid, dimethyl sulfate, methylamine and, carbon dioxide are the main used substrates in the methanogenesis process of AD.

3.2. Methane-Producing Bacteria

There are certain bacteria used in methane production. However, these types of microorganisms can be classified into two major categories; hydrogenophilic and acetophilic bacteria. The methane gas production occurs by the reduction of H_2/CO_2 by hydrogenophilic bacteria, and by the decarboxylation of acetate by acetophilic bacteria.

3.3. The Main Factors in the Production of Biogas

Certain factors influence the generation of biogas, such as sublayer composition, retention time, fermentation medium pH, temperature, pressure, volatile fatty acids (VFAs), biomass quality, loading, and toxicity [10, 13].

3.4. Methane Production Problems

Presence of toxic substances in organic waste: ammonia in high concentrations in livestock waste prevents the production of methane gas. The maximum permissible limit in the production process is about 1500ppm. Table 2 shows ammonia concentrations and their effect on the bio-methane production process [16].

Process: there are many problems related to the process like, substrate-to-inoculum ratio, inoculum storage and, inoculum dilution [17].

Table 2. The relationship between methane productivity and the concentration of the ammonia [16].

Ammonia concentration (mg/l)	Effect
5-200	Useful
200-1000	No negative impact
1500-3000	Probable inhibition at high pH
Above 3000	Poisonous

4. Digester Facilities Types

There are many types of digester facility that differ on the feedstock's, size, process used and, location. The popular types are co-digestion plants, centralized, and on-site. Each one of these techniques can be used in different location. In single farms and several farms, onsite digestion is the suitable technique to be used. In organic waste process, the centralized system is the appropriate technique. The co-digestion technique is the one to use animal manure with other organic waste [10].

5. Production of Methane by Electrochemical Reduction of CO_2

5.1. Electrochemical Method

Electrochemical method is method used to produce the methane using electrochemical reduction of CO_2. The aim of using this method is to increase the productivity of biogas by applying a microbial electro-synthesis system (MES). To form methane gas in this method, bio cathode was used to reduce CO_2 to CH_4 by supplied protons and electrons. The microbial electro-synthesis system can generate bio-gas more than 90% CH_4 when using the water from a wastewater treatment plant [18].

Electrochemistry used here is to convert the non-energy product of the carbon dioxide to full energy product of methane. From electrochemistry perspective, the reduction occurs between electrons, protons and, carbon dioxide in the MES [19].

The electrochemical concept of carbon dioxide reduction can proceed under many conditions like batch studies, short-term experiments, buffered nutrient medium and, two-chambered systems [19]. Some experiments can occur in one single reactor by mixing up anaerobic digestion units [20]. While other studies encourage mixing up the cell of microbial electrolysis cells (MECs) and AD. The use of this mixture can occur in situ by injecting H_2 gas into the anaerobic digestion reactor for biogas improvement [21-24]. Also, other techniques are injection of hydrogen gas using ex-situ or in situ [25].

5.2. Combining MES with AD to Improve Microbial Interaction

It is recommended to increase physiological interaction between different microorganisms which usually involving methanogenic microorganisms. This method is used to complete the AD reaction and; to prevent the aggregation of volatile acids like butanoic acid and propanoic acid. Also, combining two methods such a MES with AD helps to enhance the interaction required in the electrochemical systems. Each one of these processes can play an important role; MES works as transfer electrons extracellularly through the electrochemical active microorganisms which is called exoelecrogens. This increased CH_4 yield [26, 27]. Granular activated carbons (GAC) have electrical conductivity and high surface area so it can work as the electrode in MES. Figure 2 shows a combination between MES and anaerobic digestion to raise the interactivity between diverse bacteria [15].

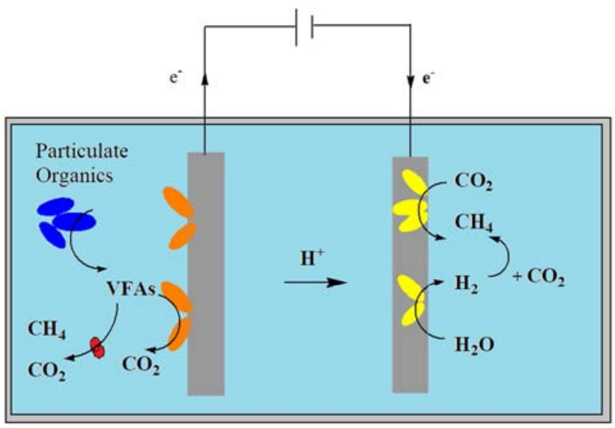

Figure 2. An illustration of bacterial interaction through the integrating effect of an MES and an anaerobic digestion process (VFAs: volatile fatty acids) [15].

6. Biogas Composition and Utilization

There are many components of the biogas including methane gas and carbon dioxide with trace quantities of nitrogen gas, hydrogen sulfide, hydrogen, ethane, propane, oxygen, and water. Table 3 represents a detailed composition of biogas [3, 15, 28, 29].

Table 3. *The percentage composition range of biogas products listed by many others [3, 15, 28, 29].*

Gas Constituent	Composition percent
Methane gas	50–75%
Carbon dioxide gas	15–60%
Nitrogen gas	0–10%
Hydrogen gas	Traces
Hydrogen sulfide gas	0–3%
Oxygen gas	0-2%
Ammonia	0–0.05
Moisture	1-5%

Biogas is used primarily in heat and power plants [2]. Before utilization, the biogas requirement is desulfurized and dehydrated to stop destruction to the gas utilization systems. Produced gas by co-fermentation of harvesting residues or energy crops with manure can be holding high concentrations of hydrogen sulfide (100 to 3000 ppm) while needs levels are below 250 ppm. So the removal of H_2S is done to prevent extreme corrosion and the high lubricating lubricant deterioration. The methane gas yield is affected by the feedstock's (50%-84.8%). in table 4 is shown the percent composition of methane gas relevant to the feedstock's [15].

Table 4. *CH_4 percentage according to different feedstock's [15].*

Feedstock	CH_4 Composition (%)
Beet leaves	84.8
Herbs	84
Straw of wheat	78.5
Straw of barley	77
Poultry waste	68
Horse dung	66
Sheep dung	65
Pig manure	60
Cattle manure	50–60
Dried leaves	58
Corn silage	54.5

7. Pretreatment Methods of Lignocellulose for Biogas Production

The pretreatment method is using in the case of the use of the lignocellulose. The lignocellulose has some outstanding treats like low biodegradability and low energy content. So these methods make the digestion process simple by converting polymer to simple ingredients. The monomer that produced out the breakage of the polymer increases the amount of the monosaccharaides and, this helps to speed up the hydrolysis rate. Table 5 shows some pretreatment methods [13, 30].

Table 5. *Lignocellulose pretreatment methods for biogas production [13, 30].*

Pretreatment method / lignocellulose changing	Processes	Important notes
Physical methods: The possible change: 1. Reduction in the cellulose crystallization and the polymerization degrees. 2. A rise in attainable area of the surface and the size of the pore.	Irradiation: Gamma-ray, electron-beam, and microwave irradiation. Other methods: Hydrothermal: extrusion, high pressure steaming, and pyrolysis, expansion.	1. Most of them required highly energy. 2. Most of the methods not effectible for the lignin removing. 3. Not favoured to use for industrial application. 4. No chemicals are generally in demand.
Chemical and physiochemical methods: The possible change: 1. Reduction in the cellulose crystallinity and the polymerization degrees. 2. A rise in attainable area of the surface. 3. Partially or semi-completely delignification. 4. Partially or totally break down of hemicellulose by chemical reaction with water.	Explosion: Ammonia fiber, steam, sulfur dioxide, and carbon dioxide explosion. Alkali: NH_3, $(NH_4)_2SO_3$, NaOH. Acid: H_3PO_4, HCl, H_2SO_4. Gas: NO_2, SO_2, ClO_2. Oxidizing agents: O_3, wet oxidation, H_2O_2.	These methods are: 1. Hopeful methods for commercial utilization. 2. The processing rate is usually fast. 3. Typically, it requires tough conditions. 4. Chemicals are required.
Biological methods: The possible change: 1. Minimizing the polymerization of the cellulose. 2. Partially break down of hemicellulose by chemical reaction with water. 3. Delignification.	Fungi and Actinomycetes	For these methods, the: 1. Energy requirement is low. 2. Chemical are required. 3. Environmental conditions are mild. 4. Treatment rate is very low. 5. Commercial applications did not consider.

8. Advantages and Disadvantages of Methane Generation Process

Advantages: there are numerous advantages related to the anaerobic bio-methane gas production process. The essential advantage is that the production of bio methane gas, which used as energy source. Digested waste has used as fertilizer [10, 11, 16, 28]. Energy consumption, nutrient, and chemical requirement for AD systems are low [11, 16]. Reduction of solids to be handled, facilitation of sludge dewatering, raw waste stabilization [11], improved sanitation [28], and reduced the odor of well-digested livestock waste [10, 11, 16]. More benefit advantages are reduction of the greenhouse emissions, nitrous oxide emissions, pathogens, and disease transmission [10, 28]. Other advantages of the AD system as compared to other conventional systems are low space requirements [11], applied to big or small areas [3], operating costs are relatively very low [3, 11, 28]. At the end, stabilization of the excess sludge results in limited environmental impact [3].

Disadvantages: The first disadvantage is longer startup period as compared to aerobic systems [3, 11]. Also, methane storage and liquefaction need high costly and specific equipment [16].

There are more disadvantages like, high buffer requirements for the pH control (6.5–8.) [3], and if sulfide compounds are present in the digestion medium, a treatment step is needed to convert sulfide to elemental sulfur [11]. Likewise, the high sensitivity of microorganisms to pH and temperature affects the process [3, 11]. AD system requires reliable feed source, very good hygiene of sludge from mesophilic digestions, a reliable outlet for treating sludge [28]. Furthermore, disadvantages of the anaerobic digestion process are, high construction relative to many potential users, laborious operation and maintenance, and less suitable in cold and arid regions [28].

9. Biogas Future

By looking at the providence of biogas, many influents that can affect the biogas economy involve the properties of a product, availability of the waste, and efficiency of the digestion process. The lignocellulose wastes are not expensive and available for bio gas production. Also, registration of the methane gas produces from cellulose as a renewable source of fuel (bio-methane). In 2030 will be many feedstock's resources for biogas production besides the sewage sludge, such as residues of the food processing, landfill, and wet manure [7].

10. Conclusion

The production of bio-methane gas through anaerobic digestion of biomass is one of the best ways of the methane gas production, and it's considered a source of renewable energy.

Produced bio-methane gas had been used in many fields of energy.

The process of producing methane gas is carried out through several steps represented by acidogenesis, hydrolysis, acetogenesis, and methanogenesis. These steps are done using acetogenic, acidogenic, and methanogenic bacteria.

Biogas productivity can be increase by combining a microbial electro synthesis system with anaerobic digestion systems.

Pretreatment methods as physical, chemical, Physiochemical, and biological were proceeded to break the complex substrates, into simple components.

Many influences influence the parameters of biogas as the kind of biomass, toxicity of nutrition, temperature inside the digester, and pH of the medium.

There are potential problems with an anaerobic digester like toxic components in waste, and processes related to inoculum storage, dilution, and inoculum-to-substrate ratio.

The anaerobic digestion has many advantages besides methane generation. Some of these advantages are low energy consumption, low nutrient, low chemical requirement, improved sanitation, reduced pathogens, reduced disease transmission, reduced greenhouse emissions, and reducing nitrous oxide emissions. However, the disadvantages of the AD can be summarized in the following; longer startup period as compared to aerobic systems, require high buffer to pH control, high sensitivity of microorganisms to pH and temperature, requires a reliable feed source, requires very good hygiene of sludge from mesophilic digestions, and a reliable outlet for treating sludge.

In the future will study the alternative of the high buffer require for pH controlling and testing the reliability of the feed sources.

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