International Journal of Environmental Science and Green Technology
https://journals.ayu.edu.kz

The Prospects of Using Biogas: Technological Achievements, Ecological and Economic Efficiency, Development in Global Energy

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Keywords

Biogas
Methane
Energy
Organic Waste
Anaerobic Decomposition

Abstract

This article examines various aspects related to biogas production, its technological features, economic advantages, and the challenges faced by the industry. Biogas, as an important renewable energy source, is a mixture of methane (CH_4) and carbon dioxide (CO_2) that forms during the anaerobic decomposition of organic materials. With the increasing environmental and economic issues associated with the use of fossil fuels, biogas has become a promising solution for reducing carbon emissions and recycling waste. The article analyzes global trends, current statistical data, and prognostic conclusions about the development of the biogas sector in the coming decades. It also focuses on the current state of biogas production in the world and Kazakhstan, as well as the potential for expanding this sector in the context of sustainable development.

Cite

Akhmetov, N. & Yuldashbek, D. (2025). The Prospects of Using Biogas: Technological Achievements, Ecological and Economic Efficiency, Development in Global Energy. IJES & GreenTech, 1(1), 14-. doi:

Article Process

Submission Date: 16.01.2025; Revision Date: 10.02.2025; Accepted Date: 23.02.2025; Published Date: 25.03.2025;

1. INTRODUCTION

In recent years, the depletion of fossil energy resources has increased the importance of reducing dependence on them. A significant increase in energy consumption, driven by population growth, has led to a high daily demand for energy [1]. The transition to renewable energy sources has become a necessity and is of key importance [2]. Increasingly, the valorization of agricultural waste for energy production and nutrient recovery is being considered as an effective and sustainable solution [3].

Clean energy sources, such as solar, wind, hydroelectric power, and biomass, have become relevant in response to the growing global demand for sustainable and environmentally friendly energy sources. Among these technologies, biomass has significant potential as an alternative energy source capable of replacing fossil fuels [4].

Biomass refers to organic materials, such as agricultural waste, forestry by-products, and specially grown energy crops, that can be converted into energy through various methods. Biomass conversion into energy can be carried out through combustion, gasification, or biochemical conversion. One of the promising directions for biomass utilization is anaerobic digestion, a process in which organic substances are broken down by microorganisms in the absence of oxygen, leading to the production of biogas [5].

Biogas is a mixture of methane, carbon dioxide, and other gases formed during the anaerobic decomposition of organic matter. This process occurs in sealed containers called bioreactors, where organic material (such as manure, agricultural waste, or food scraps) undergoes decomposition without oxygen [6] (Figure 1). Methane, the primary component of biogas, is a valuable energy source that can be used for electricity and heat generation, as well as for transportation needs in the form of biomethane [7-8].

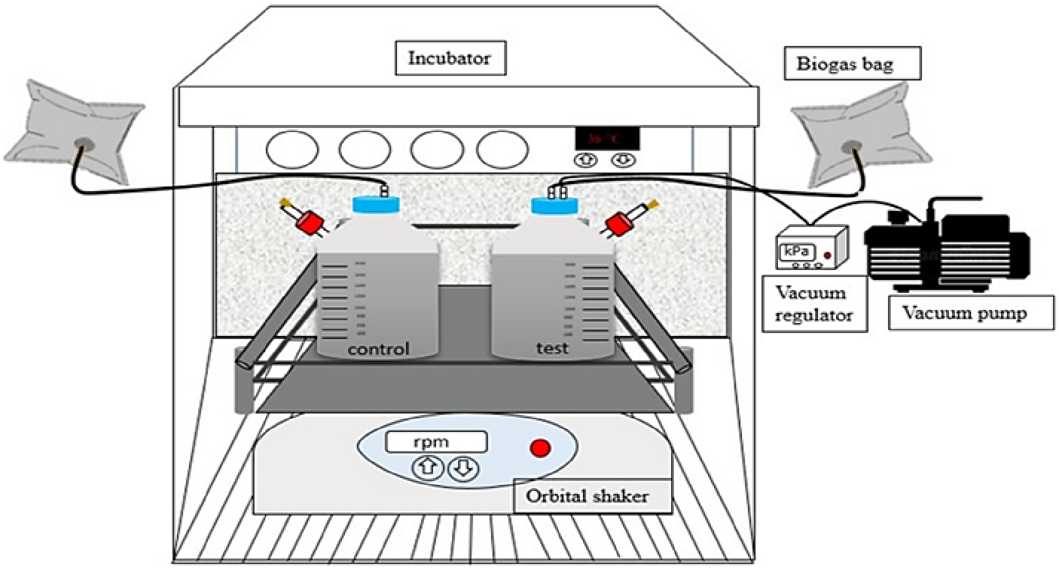

Figure 1. *Anaerobic reactor installation [9]*

In recent decades, there has been a rapid growth in interest in biogas as an energy source, driven by the need to reduce climate impact, decrease greenhouse gas emissions, and address the waste problem [10]. Biogas is also seen as an alternative fuel source for agriculture and industry, contributing to solving several environmental issues simultaneously. One of the greatest advantages of biogas is its ability to convert waste into useful energy, thus not only saving resources but also improving the environmental situation [11].

However, despite these advantages, biogas production requires significant investment in technological facilities and infrastructure. At the same time, the efficient use of biogas on a global scale could be a decisive factor in the transition to sustainable energy sources, supported by government assistance and international initiatives. It is also important to note that biogas is not the only renewable energy source, and its use should be harmoniously integrated with other solutions to create a sustainable energy system.

The aim of this article is to provide a comprehensive analysis of the current state and trends in biogas production, examine its key technological, economic, and environmental aspects, and assess the opportunities for further industry development.

2. GLOBAL BIOGAS MARKET: TRENDS AND STATISTICS

Despite its small contribution to the overall energy balance, biogas is actively developing, and its share is expected to increase in the coming decades. This is driven not only by global initiatives to combat climate change but also by the growing demand for clean and renewable energy sources.

According to forecasts by the International Energy Agency (IEA), biogas production is expected to reach 200 billion cubic meters per year by 2030 [12]. This growth is driven by several factors, including the decreasing cost of biogas production, improvements in waste recycling technologies, and the increased use of biomethane in transportation. Unlike other renewable energy sources, such as solar and wind energy, biogas has the unique ability to produce a stable amount of energy year-round, making it especially valuable in the energy landscape.

According to Global Biogas Market data, the highest number of biogas production facilities are located in economically developed countries such as Germany, the United Kingdom, and the United States. However, developing countries are also actively increasing their capacities in this area [13]. In recent years, China, India, and Brazil have significantly increased their biogas production due to the large amount of organic waste available for recycling [14]. This market growth opens new opportunities for investors, offering chances to invest in eco-friendly and sustainable energy projects.

On the international stage, biogas production is developing quite dynamically, especially in countries with developed agriculture and high environmental safety standards. In 2020, global biogas production reached over 80 billion cubic meters, with Europe, China, and the United States being the main leaders in this field [15] (Table 1).

Table 1. Biogas Production Volumes by Country (2020)

Country	Number of Installations (units)	Production (billion m^3)	Share in Global Production (%)
Germany	10,000	5.0	6.25
China	30,000	2.5	3.125
USA	2,200	3.8	4.75
India	1,500	1.0	1.25
United Kingdom	500	0.8	1.0

European Union. European countries are leaders in biogas production, where anaerobic digestion technologies are actively applied in both agriculture and utilities. Germany is one of the largest biogas producers in Europe, with around 10,000 biogas installations operating within its territory [16]. The majority of biogas is used for electricity and heat generation, as well as for the production of biomethane, which is used as fuel for vehicles [17].

China. China also holds a leading position in biogas production. In recent years, China has increased the number of biogas installations, especially in rural areas, where methanogenesis technologies are used to process livestock and agricultural waste. The advantage of Chinese technologies is the integration of biogas plants with agricultural farms, which allows for the efficient recycling of organic waste while simultaneously generating energy [18].

USA. In the United States, biogas is actively used in the energy sector, particularly in agriculture. Technologies for waste recycling aimed at electricity generation are also being implemented. In recent years, there has been a growing interest in biogas as an alternative energy source, driven by the need to reduce greenhouse gas emissions and the development of renewable energy sources [19].

3. BIOGAS PRODUCTION STATISTICS IN KAZAKHSTAN

In Kazakhstan, biogas production is still in the developmental stage; however, in recent years, there has been growing interest in using this renewable energy source. The country has significant potential due to its vast agricultural and livestock resources, which create favorable conditions for the development of the biogas industry [20].

Existing Projects and Prospects. Several biogas installations are currently operating in Kazakhstan, mainly focused on processing organic waste generated in agriculture. One notable example is a project for processing livestock waste at agricultural enterprises in the Almaty and Pavlodar regions [21]. These installations are used to produce energy and fertilizers from manure and other organic waste.

The prospects for biogas production in Kazakhstan are linked to the growing interest in clean energy, the establishment of additional installations, and the development of policies to support renewable energy sources. In the future, biogas could become an important part of the country's energy landscape, especially in the context of sustainable development [22].

4. RAW MATERIALS FOR BIOGAS PRODUCTION

The process of biogas production is made possible by using various organic materials that can undergo anaerobic decomposition, meaning decomposition in the absence of oxygen. Different types of raw materials have different potential for biogas production, which depends on their chemical composition, carbon and nitrogen content, as well as physicochemical characteristics [23]. Let’s consider the most commonly used materials for biogas production.

Agricultural Waste. Agricultural waste, including straw, leftover feed, and plants, which are carbon-rich materials, are among the most common types of raw materials for biogas plants. These materials provide high biogas yields because they contain a large amount of organic matter, which can be decomposed by microbes during anaerobic digestion [24].

Livestock Waste. One of the most traditional and effective raw materials for biogas production is manure and poultry litter. Livestock waste has a high carbon and nitrogen content, which creates favorable conditions for the active work of microorganisms involved in anaerobic decomposition. It is also worth noting that processing manure into biogas significantly reduces environmental pollution that can occur from its uncontrolled accumulation and decomposition in open areas [25].

Food and Municipal Waste. Food waste, which remains after the processing and consumption of food products, is another promising source for biogas production. These wastes contain carbohydrates, proteins, and fats, which are excellent raw materials for methanogenic bacteria (Figure 2). Additionally, the organic fraction of solid municipal waste can also be processed into biogas, addressing the issue of household waste disposal and producing energy from organic materials that would otherwise end up in landfills [26-27].

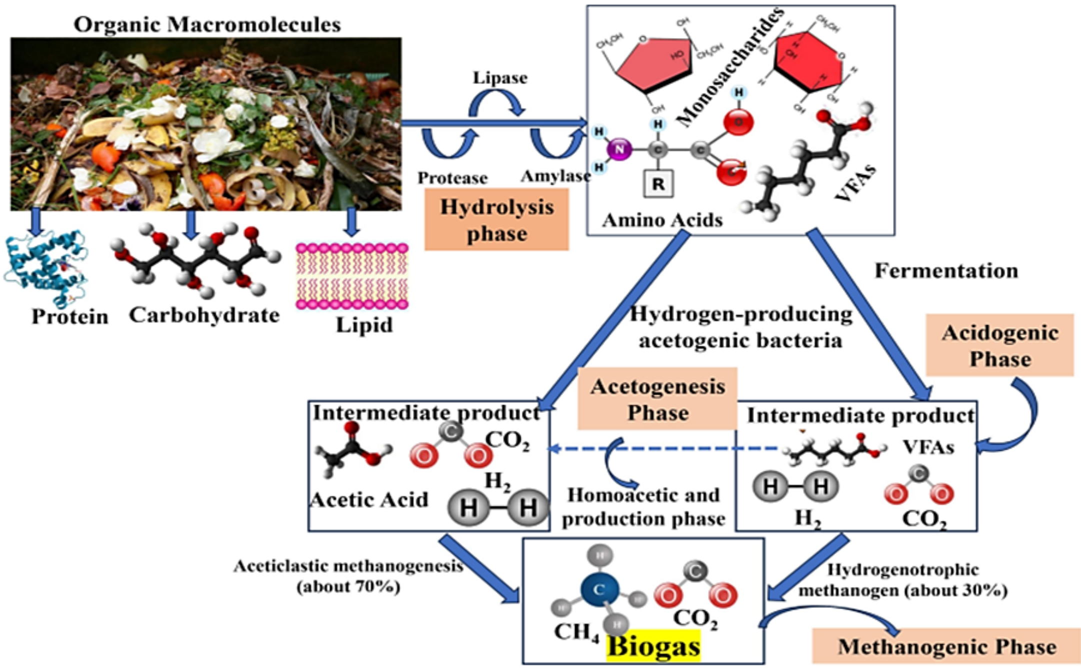

Figure 2. *Different Stages of Anaerobic Digestion of Food Waste [28]*

Forest and Wood Waste. Wood waste, such as chips, leaves, and remnants from wood processing, can also be used for biogas production. However, unlike agricultural waste, the effective use of wood materials requires prior grinding and preparation, as lignin and cellulose take more time and effort to be processed by microorganisms [29].

5. METHODS OF BIOGAS PRODUCTION

The process of biogas production involves the *anaerobic decomposition* of organic matter, during which organic feedstock is converted into a mixture of methane (CH_4), carbon dioxide (CO_2), and other gases such as hydrogen, hydrogen sulfide, and ammonia [30-31], (Figure 3).

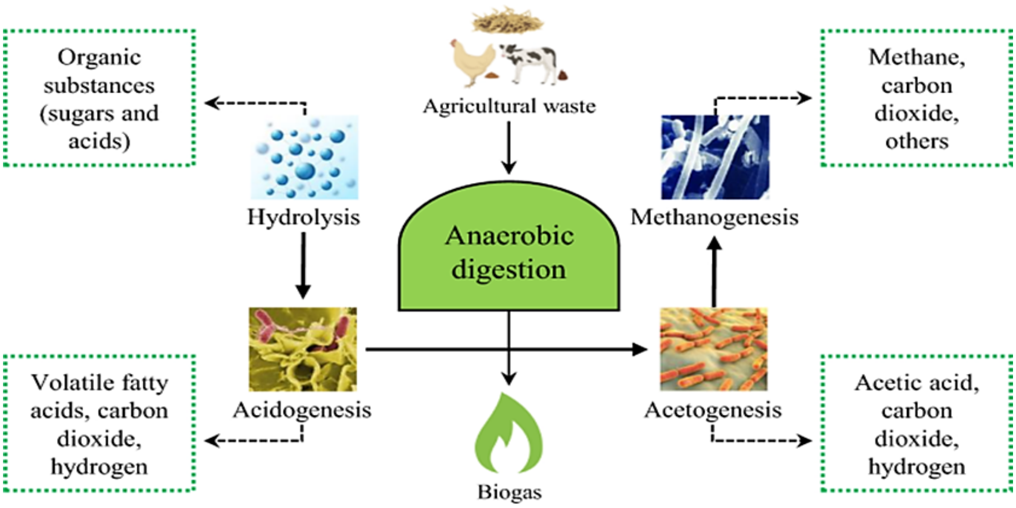

Figure 3. *Overview of Biogas Production and Anaerobic Digestion Processes [32]*

This process occurs in several phases, each involving specific biochemical reactions initiated by microorganisms. Biogas production methods can vary depending on the type of feedstock and technology used, but the process generally consists of the following stages:

Hydrolysis. Hydrolysis is the initial stage of anaerobic decomposition, during which macromolecules of organic feedstock (cellulose, proteins, fats) are broken down into simpler compounds: monosaccharides, amino acids, and fatty acids. This process occurs with the involvement of hydrolyzing bacteria, which can break down complex polymers into smaller, soluble components [33]. Hydrolysis is necessary to make the molecules available to other bacteria involved in the process.

Acid Fermentation (Fermentation Phase). After hydrolysis, the resulting soluble components (sugars, amino acids) undergo fermentation. In this stage, carbohydrates, proteins, and fats are broken down into organic acids (acetic, propionic, and butyric acids), as well as alcohols (e.g., ethanol) [34]. These organic acids are intermediate products that are subsequently used by methanogenic bacteria to synthesize methane. Acidic bacteria, such as *Clostridium* and *Bacteroides*, convert carbohydrates and proteins into organic acids and volatile fatty acids, which then react with methanogenic bacteria [35].

Methanogenesis. Methanogenesis is the final phase of the biogas process, during which the organic acids formed during fermentation are converted into methane and carbon dioxide. This process is carried out by methanogenic bacteria. They use organic acids or alcohols, during which gases are released, with methane (CH_4) being the primary product [36]. Methanogenesis occurs under anaerobic conditions, as methanogenic bacteria are sensitive to oxygen and cannot function in its presence. This stage is crucial for biogas formation, and its completion results in a gas mixture containing approximately 50-70% methane [36].

To increase the efficiency of these stages, biogas plants maintain optimal temperature conditions (35-40°C) and an acid-base balance (pH 6.8-7.5), which promotes the active activity of methane-producing bacteria [36].

Impurity Removal. Once biogas is produced, it can be further purified from hydrogen sulfide, ammonia, and other impurities. This is done using various methods, such as hydrogen sulfide absorption using activated carbon or hydroxides, as well as carbon dioxide separation, to increase the methane content in the product.

6. TYPES OF BACTERIA INVOLVED IN BIOGAS PRODUCTION

The process of anaerobic decomposition of organic materials cannot occur without the participation of bacteria, each of which plays its role at different stages of the decomposition process [37]. Several types of bacteria actively participate in the biogas production process:

Hydrolyzing Bacteria. Hydrolyzing bacteria are microorganisms that initiate the decomposition of organic feedstock. These bacteria break down large molecules (such as cellulose, lignin, and proteins) into simpler components – monosaccharides, amino acids, and fatty acids. Hydrolyzing bacteria play an important role in the first stage of organic matter decomposition, converting large molecules into soluble components that can be used by subsequent microorganisms: *Bacillus, Clostridium, and Bacteroides* [38].

Acidogenic Bacteria. After the organic matter has undergone hydrolysis, it is converted into organic acids with the participation of acidogenic bacteria. At this stage, substances such as acetic acid, propionic acid, butyric acid, and alcohols are formed. These organic acids are intermediate products, which will then be used by methanogenic bacteria to produce methane. Acidogenic bacteria also participate in the production of volatile fatty acids, such as acetic and butyric acids [39]. Examples of acidogenic bacteria include *Clostridium, Propionibacterium, and Lactobacillus.*

Methanogenic Bacteria. Methanogenesis is the process in which organic acids and alcohols are converted into methane and carbon dioxide. These bacteria play a key role in biogas formation. Methanogenic bacteria are strictly anaerobic, meaning they function only in the absence of oxygen. These microorganisms are capable of using products such as acetic acid and hydrogen to synthesize methane [40]. Examples of methanogenic bacteria include *Methanobacterium, Methanosarcina, and Methanococcus.*

Methanogenesis is the most crucial stage in biogas formation because methane (CH_4) is the primary component of biogas, which is used for energy generation [40].

7. APPLICATIONS OF BIOGAS

Due to its high methane content, biogas can be used in various fields, including energy production, transportation, agriculture, and eco-economic projects.

Energy Production. Biogas is actively used for electricity and heat generation. In biogas plants, methane is burned to produce electrical energy, which can be used to supply both industrial facilities and residential areas. The heat generated from burning biogas can be used for building heating and industrial processes [41].

Biogas plants efficiently utilize organic waste (e.g., agricultural or household waste), converting it into an energy source. In countries with developed technologies, biogas plants are becoming an integral part of the energy infrastructure, ensuring sustainable and clean energy production [41].

Transportation. Biogas, specifically methane, can be purified and converted into *biomethane,* a gas that is similar to natural gas and can be used as fuel for vehicles. Biomethane is used in specialized engines, enabling vehicles to operate more environmentally friendly with minimal carbon dioxide and other harmful emissions [42].

Methane derived from biogas is increasingly used as fuel for buses, trucks, and even private cars, helping to reduce dependence on fossil hydrocarbons and decreasing greenhouse gas emissions into the atmosphere [42].

Agriculture. One of the key products of organic waste processing into biogas is *digestate,* the residual mass after anaerobic decomposition. Digestate is a nutrient-rich fertilizer that can be used in agriculture to improve soil quality. This fertilizer contains essential elements such as nitrogen, phosphorus, potassium, and trace elements necessary for plant growth [43].

The use of digestate helps significantly reduce the need for chemical fertilizers, improving soil fertility and promoting sustainable agriculture [43].

Eco-friendly Waste Disposal. One significant advantage of biogas production is the efficient disposal of organic waste that would otherwise end up in landfills, releasing methane, a potent greenhouse gas. Recycling waste into biogas not only reduces the environmental burden but also addresses pollution issues by cutting emissions into the atmosphere [44].

Biogas plants are an important tool for processing organic waste, including agricultural waste, food industry waste, and household and municipal waste, contributing to an improved environmental situation [44].

Industrial Applications. In addition to energy use, biogas can be applied in the chemical and food industries. It is used to supply heat for technological processes (such as drying or heating) and for processing organic waste generated during production [45].

8. ECONOMIC ASPECTS OF BIOGAS PRODUCTION

The biogas production process requires significant capital investment for the construction of the plant; however, in the long term, it can be economically advantageous due to the revenue from selling the produced energy and reducing waste disposal costs. The cost of biogas plants varies depending on the capacity and technologies used at each specific facility. For example, a plant with a capacity of 1 MW can cost between 1 to 3 million USD, making this type of energy accessible for both large enterprises and small farm businesses, especially considering government subsidies and tax incentives [46] (Table 2).

Table 2. *Cost of Construction and Operation of Biogas Plants.*

Type of Plant	Construction Cost ($)	Operational Lifetime (years)	Processing Cost (per m^3)
Small plants (<1 MW)	1,000,000 - 1,500,000	15-20	0.08
Medium plants (1-5 MW)	1,500,000 - 3,000,000	15-25	0.06
Large plants (>5 MW)	3,000,000 - 5,000,000	25-30	0.05

One of the significant factors affecting the economic efficiency of biogas production is the choice of raw materials. For example, using agricultural waste can significantly reduce processing costs, as these materials are often readily available and inexpensive. However, for large-scale projects, the cost of constructing and operating biogas plants can be quite high, and effective infrastructure for collecting, transporting, and processing organic waste is essential for their successful operation.

Moreover, the stability of production is crucial for the successful operation of biogas plants. Biogas plants require regular replenishment of raw materials, which is linked to ensuring a continuous supply of organic waste. In countries with highly developed agricultural sectors, such plants can be economically viable, as they not only handle waste recycling but also provide additional income for agricultural enterprises.

9. ENVIRONMENTAL AND SOCIAL ASPECTS

Biogas installations have a significant impact on the environment by helping to reduce greenhouse gas emissions. Traditionally, organic waste decomposes in landfills and releases methane into the atmosphere, contributing to global warming. The use of biogas allows for the disposal of these wastes while producing clean energy, significantly reducing the carbon footprint [47].

Biogas installations also play a key role in solving the waste problem, especially in agriculture. Organic waste, such as manure and plant residues, represents a large amount of biodegradable materials that can become a source of pollution if not properly disposed of. Biogas installations offer a solution to this problem by converting waste into useful energy while simultaneously reducing pollution [48].

The social and economic effects of biogas use are also significant. In developing economies, such technologies can create jobs and contribute to the development of local economies. This is especially relevant in rural areas, where local resources can be used to generate energy and reduce fuel costs [49].

10. DEVELOPMENT PROSPECTS

The prospects for the development of the biogas sector are very optimistic. According to forecasts, biogas production will continue to grow, with an increase in the number of installations and the implementation of more efficient technologies. In countries with developed economies, biogas will be actively used for electricity generation, as well as for replacing natural gas in industry and transportation. Biogas technologies will continue to improve, which will significantly reduce production costs and increase methane yield [50].

In countries with emerging markets, biogas will become an important tool for addressing the waste problem and ensuring energy security. The growing population and increasing volume of waste create a need for large-scale biogas utilization, which, in addition to everything, is an affordable and environmentally clean energy source [50].

11. CONCLUSION

In the context of the growing global demand for renewable energy, biogas represents one of the most promising technologies for addressing energy security and sustainable development challenges. Due to its environmental and economic advantages, biogas can become a crucial element in the transition to more sustainable energy sources, particularly in agriculture and industry. It is expected that, in the coming decades, biogas will play a key role in the energy systems of many countries, driving economic growth and improving environmental conditions.

Biogas is a highly efficient and environmentally clean energy source that helps solve several pressing issues, such as waste disposal, reduction of greenhouse gas emissions, and ensuring sustainable energy development. In Kazakhstan, the biogas industry has significant growth potential, linked to the availability of large amounts of agricultural and livestock waste. In the future, biogas could become an important element in ensuring energy security and sustainable development in our country.

AUTHOR CONTRIBUTIONS

Writing-review & editing, methodology, supervision: Nurlan Akhmetov; conceptualization, writing-review & editing, data curation: Davlat Yuldashbek.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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