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CONTENTS

PLATFORM MIDDLEWARE-MANAGEMENT: FROM RESOURCE CONTROL TO INTERACTION COORDINATION IN DIGITAL SERVICE ECOSYSTEMS.....	8
Ilgor Abdullayev	
APPROACHES TO IMPROVING KNOWLEDGE EXCHANGE PROCESSES IN INDUSTRIAL CLUSTERS.....	16
Mamadaliyev Anaxxon Ziyodillayevich	
IMPROVING EXPENDITURE ACCOUNTING IN HIGHER EDUCATION INSTITUTIONS	21
Islom Ergash ugli Khonimqulov	
MANAGEMENT OF FOREIGN EXCHANGE AND CONCENTRATION RISKS IN THE OPERATIONS OF COMMERCIAL BANKS	26
Qurbonov Ilhom Jumaqulovich	
WAYS TO IMPROVE THE USE OF NATURAL RESOURCES IN THE DEVELOPMENT OF HEALTH SERVICES.	29
Sobirov Kayum Xamraevich	
REGIONAL BANKING MARKET TRENDS FOR RETAIL DEVELOPMENT	33
Salamov Islom Tashqazaqovich	
REFORMS UNDERTAKEN IN THE REPUBLIC TO INCREASE PRODUCTION CAPACITY AT FOOD INDUSTRY ENTERPRISES	37
Gulmatov Sunnatillo Nurillayevich	
PROSPECTS FOR USING ISLAMIC FINTECH TECHNOLOGIES IN SMALL BUSINESS FINANCING IN UZBEKISTAN	44
Toshxo'jayev Abduqodirxon Abdulmansurxon ugli	
ADAPTIVE CONCEPT OF HUMAN CAPITAL MANAGEMENT: A NEW PARADIGM FOR SUSTAINABLE ECONOMIC GROWTH	51
Dinora Qudrat qizi Yusubboyeva	
MECHANISMS FOR ENHANCING EDUCATION SERVICE QUALITY IN DEVELOPING YOUTH ENTREPRENEURSHIP IN THE ARAL SEA REGION.....	58
Raxmanov Raxmanbergan Abdullayevich	
CONCEPTUAL FOUNDATIONS OF IMPLEMENTING AGILE MANAGEMENT IN PUBLIC ADMINISTRATION	62
Sayfiyev Jasur Ravshanovich	
SCIENTIFIC PERSPECTIVES OF WORLD, EUROPEAN, AND CIS SCHOLARS ON ENTREPRENEURSHIP DEVELOPMENT AND FINANCIAL SUPPORT: A COMPARATIVE ANALYSIS	70
Inobatov Abror Boshlarovich	
SUSTAINABILITY REPORTING AND ESG AUDITING: EMERGING TRENDS IN CORPORATE ACCOUNTABILITY.....	84
Turabekov Bekali, Eshpulatova Zaynab	
ИНДИКАТОРЫ ОЦЕНКИ И МОНИТОРИНГА РАЗВИТИЯ ЖЕНСКОГО ПРЕДПРИНИМАТЕЛЬСТВА В УЗБЕКИСТАНЕ	91
Хусанова Зулфия Рахматуллаевна	
A METHODOLOGICAL APPROACH TO DIGITALIZING INTERNAL AUDIT IN COMMERCIAL BANKS BASED ON THE CONTINUOUS AUDITING CONCEPT	95
Narziyev Xayotjon Azamatovich	
AN AUTHOR'S APPROACH TO THE CLASSIFICATION OF FINANCIAL INVESTMENTS BY MEASUREMENT BASIS FOR ACCOUNTING AND AUDITING PURPOSES	102
Jumamurodov To'libay Yeldashbayevich	
ENHANCING THE CONTINUOUS MONITORING PROCEDURE FOR IDENTIFYING IMPAIRMENT INDICATORS OF NON-CURRENT ASSETS IN JOINT-STOCK COMPANIES.....	107
Fayzullayev Begzod Baxtiyor o'g'li	

THE INTERRELATIONSHIP BETWEEN MATERIALITY AND AUDIT RISK IN PUBLIC-SECTOR INTERNAL AUDITING AND THEIR APPLICATION WITHIN A UNIFIED METHODOLOGICAL FRAMEWORK.....	114
Ismatillayev Baypo'lat Xushvaqtovich	
THE NATURE, DEFINITION AND CLASSIFICATION OF INTERNAL AUDIT OF PUBLIC PROCUREMENT	122
Rajabov Shukhrat Ismayilovich	
A METHODOLOGY FOR THE COMPOSITE ASSESSMENT OF THE MATURITY OF INTERNAL AUDIT FUNCTIONS IN COMMERCIAL BANKS.....	128
Ismailov Azizbek Madaminovich	
THE ECONOMIC SUBSTANCE OF THE CONCEPT OF "RISK-BASED INTERNAL AUDITING" AND THE THEORETICAL FOUNDATIONS OF ITS APPLICATION IN LIGHT INDUSTRY ENTERPRISES	136
Shahlo Mahmatmurodovna Tojiyeva	
THE INSTITUTIONAL MECHANISM FOR THE INNOVATIVE DEVELOPMENT OF THE RAILWAY NETWORK.....	143
Muradov Bakhrom Akramjanovich	
ТЕОРЕТИЧЕСКОЕ ОПРЕДЕЛЕНИЕ ОСНОВНЫХ СТАТИЧЕСКИХ ХАРАКТЕРИСТИК ОПТОЭЛЕКТРОННЫХ ДИСКРЕТНЫХ ПРЕОБРАЗОВАТЕЛЕЙ ПЕРЕМЕЩЕНИЙ С ПОЛЫМИ И ВОЛОКОННЫМИ СВЕТОВОДАМИ.....	148
Умид Садирдинович Холматов	
ИНСТИТУЦИОНАЛЬНЫЙ РАЗРЫВ В ЗАЩИТЕ ЗАЁМЩИКОВ: ЭМПИРИЧЕСКИЙ АНАЛИЗ НАЧИСЛЕНИЯ ПРОЦЕНТОВ И НЕУСТОЙКИ ПОСЛЕ СУДЕБНОГО ВЗЫСКАНИЯ В УЗБЕКИСТАНЕ..	155
Жаксымуратов Бахрам Раджович	
PROSPECTS FOR SMALL BUSINESS DEVELOPMENT IN THE CONTEXT OF THE GREEN ECONOMY.....	164
Abdurakhimov Iskandar Nodirjon o'g'li	
DIGITAL PAYMENT ADOPTION IN TOURISM: FACTORS INFLUENCING ACCEPTANCE IN SAMARKAND, UZBEKISTAN	169
Nazarova Kamola Sultonmurod qizi	
CHANGE MANAGEMENT IN THE ADOPTION OF BIM TECHNOLOGY IN UZBEKISTAN'S CONSTRUCTION PROJECTS: A CONCEPTUAL APPROACH BASED ON THE ADKAR MODEL.....	176
Shaxlo Baxtiyor qizi G'ulomova	
SMART DESTINATIONS, SMARTER JOURNEYS: SCIENCE, INNOVATION, AND THE DIGITAL TRANSFORMATION OF GLOBAL TOURISM.....	182
Sirojiddinova Shahrizoda, Nasimov Dilmurod Abdulloyevich	
SELECTION OF INPUT MAGNITUDE FOR INVESTIGATING KINEMATIC AND STRUCTURAL PARAMETERS OF VSH PTM ELLIPTICAL DRUM COTTON PICKING APPARATUS	186
Abdazimov Anvar, Ravutov Shavkat, Rajapbayev Umidjon	
BIOGAS GENERATION AND PRACTICAL IMPLEMENTATION IN UZBEKISTAN: TECHNOLOGICAL ASPECTS AND STATISTICAL ASSESSMENT	191
Eshbekov Mukhriddin, Khudoyqulov Zokir	

BIOGAS GENERATION AND PRACTICAL IMPLEMENTATION IN UZBEKISTAN: TECHNOLOGICAL ASPECTS AND STATISTICAL ASSESSMENT

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Abstract. This article analyzes the technological aspects and statistical metrics of biogas generation and its practical implementation within Uzbekistan's green energy framework. The study evaluates the substantial potential for recovering energy from agricultural and industrial organic waste under local conditions. Special emphasis is placed on assessing the efficiency of advanced biogas upgrading systems, specifically Autogenerative High-Pressure Digestion (AHPD) and Pressure Vacuum Swing Adsorption (PVSA). Furthermore, the role of biomethane in ensuring energy security, mitigating environmental impacts, and enhancing economic efficiency is thoroughly examined. Based on the statistical assessment and research findings, practical recommendations are proposed to accelerate the development of the sustainable biogas sector in Uzbekistan.

Key words: biogas generation, practical implementation, technological aspects, statistical assessment, AHPD, PVSA, renewable energy.

INTRODUCTION.

Energy security and climate change are among the most pressing global challenges of the twenty-first century. In this context, the use of renewable energy sources has become an important strategy for reducing greenhouse gas emissions and promoting sustainable economic development. Biogas is a combustible gas produced through the anaerobic digestion of agricultural residues, livestock manure, household waste, and industrial organic waste. It mainly consists of methane (CH₄) and carbon dioxide (CO₂). Biogas can be used as a renewable energy source for electricity and heat generation, while the digestion residue can be processed into biohumus, a valuable organic fertilizer for agricultural applications [1].

Uzbekistan has identified the transition to a green economy and the expansion of renewable energy utilization as priority directions within its national sustainable development strategy. In this regard, biogas technologies provide significant opportunities for the efficient utilization of large volumes of organic waste generated in the agricultural and municipal sectors. The country possesses considerable biomass resources, particularly in regions with intensive livestock farming and agro-industrial activities [12].

Therefore, the aim of this study is to assess Uzbekistan's biogas production potential and investigate modern technological solutions for improving biogas utilization efficiency. Special attention is given to advanced biogas upgrading technologies, namely **Autogenerative High-Pressure Digestion (AHPD)** and **Pressure Vacuum Swing Adsorption (PVSA)** [5]. The study evaluates their operating principles, technical advantages, and potential applicability under the conditions of Uzbekistan to identify effective approaches for increasing biomethane production and supporting the development of a sustainable biogas sector.

Unlike previous studies, which have mainly focused on individual biogas technologies or general biomass resources, this study provides an integrated regional assessment of Uzbekistan's biogas production potential and comparatively evaluates the applicability of AHPD and PVSA technologies under local conditions. The findings contribute to identifying efficient technological pathways for biomethane production and support the country's transition toward a sustainable green energy system.

LITERATURE REVIEW

Recent scientific publications, technical reports, and international experience demonstrate that biogas production and upgrading technologies play an increasingly important role in the development of sustainable energy systems. Previous studies have highlighted the significant potential of converting agricultural residues, livestock manure, and other organic waste into renewable energy through anaerobic digestion. Furthermore, advanced biogas upgrading technologies, particularly **Autogenerative High-Pressure Digestion (AHPD)** and **Pressure Vacuum Swing Adsorption (PVSA)**, have been recognized as effective solutions for improving biomethane quality and enhancing the overall efficiency of biogas utilization. These studies provide a valuable scientific foundation for assessing the applicability of modern biogas technologies under the conditions of Uzbekistan.

RESEARCH METHODOLOGY

This study is based on the analysis of recent scientific publications, technical reports, and international experience in the field of biogas production and upgrading technologies. The main research methods include a literature review, comparative analysis, and regional statistical assessment.

The biogas production potential was estimated for the economically active regions of **Tashkent, Fergana, and Surkhandarya** using data on agricultural residues and livestock manure generation. The assessment considered the quantity of available organic waste and its potential for anaerobic digestion.

In addition, the operating principles, advantages, and limitations of advanced biogas upgrading technologies, including **AHPD** and **PVSA**, were examined. Their technical feasibility and prospects for implementation under the climatic and economic conditions of Uzbekistan were also evaluated.

ANALYSIS AND RESULTS

Regional Assessment of Biogas Potential

The analysis indicates that several regions of Uzbekistan possess significant potential for biogas production due to the large volumes of organic waste generated by agricultural and industrial activities.

Tashkent Region: Owing to the high concentration of industrial enterprises, poultry farms, and livestock complexes, this region has the highest estimated biogas production potential. The annual production potential is approximately **130 million m³** of biogas.

Fergana and Surkhandarya Regions: These regions also possess substantial biomass resources associated with intensive agricultural development. Their estimated annual biogas production potential ranges from **95 to 110 million m³**.

These findings demonstrate that Uzbekistan has a strong resource base for developing a national biogas industry and expanding renewable energy production [8].

To mathematically evaluate the regional biomethane capacity, the total annual biogas volume (V_{biogas} , m³/year) is modeled based on the available biomass substrate types using Equation (1):

$$V_{biogas} = \sum_{i=1}^n (M_i \cdot TS_i \cdot VS_i \cdot Y_i) \cdot \eta_{local} \quad (1)$$

where M_i represents the annual mass of the organic substrate (tons/year), TS_i is the total solids content (%), VS_i denotes the volatile solids fraction (%), Y_i is the specific biogas yield (m³/ton VS), and η_{local} is the localized environmental efficiency correction factor (**0.85–0.92**) for Uzbekistan's climatic conditions.

The calculated baseline statistical parameters for the priority regions are presented in **Table 1** [2].

Table 1. Regional Biomass Resources and Raw Biogas Generation Potential in Uzbekistan

Priority Region	Biomass Potential (Tons/year)	Annual Biogas Capacity (Million m ³)	Estimated (CO ₂ Mitigation (Tons CO ₂ -eq/year)	Payback Period (Years)
Tashkent	5,050,000	130.0	245,000	3.4
Surkhandarya	5,000,000	110.0	210,000	3.8
Fergana	4,050,000	95.0	185,000	4.1
Total	14,100,000	335.0	640,000	3.8

Advanced Biogas Upgrading Technologies

To utilize biogas as a high-quality renewable fuel, it must be upgraded by increasing its methane (CH_4) concentration and removing impurities such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), moisture, and other trace gases. Biogas upgrading significantly improves fuel quality, increases its calorific value, and enables its application in transportation, electricity generation, and natural gas distribution networks. Among the available upgrading methods, **Autogenerative High-Pressure Digestion (AHPD)** and **Pressure Vacuum Swing Adsorption (PVSA)** have attracted increasing attention because of their high efficiency and environmental benefits.

Autogenerative High-Pressure Digestion (AHPD)

Autogenerative High-Pressure Digestion (AHPD) is an innovative anaerobic digestion technology in which biogas is produced directly under elevated pressure, typically ranging from **10 to 30 bar**, inside the digester. Unlike conventional anaerobic digestion systems, AHPD eliminates or substantially reduces the need for external gas compression, thereby decreasing overall energy consumption and simplifying the biogas upgrading process. In addition, the elevated operating pressure enhances the dissolution of carbon dioxide in the liquid phase, resulting in a higher methane concentration in the produced biogas [4].

The main advantages of AHPD include:

High methane concentration: The methane (CH_4) content can reach up to **96%**, allowing the production of high-quality biomethane suitable for energy applications.

Lower operational costs: Since biogas is generated under pressure, the demand for additional gas compression equipment and separate upgrading units is reduced, leading to lower investment and operating costs.

Improved environmental performance: A considerable proportion of carbon dioxide remains dissolved in the digestate, thereby reducing greenhouse gas emissions and improving the environmental sustainability of the process.

These characteristics make AHPD a promising technology for medium- and large-scale biogas plants seeking higher energy efficiency and lower operational costs [6].

Pressure Vacuum Swing Adsorption (PVSA)

Pressure Vacuum Swing Adsorption (PVSA) is an advanced gas separation technology that uses highly selective adsorbent materials, such as metal-organic frameworks (MOFs), activated carbon, or zeolite-based adsorbents, to efficiently separate carbon dioxide (CO_2) from biogas. The process operates through alternating pressure and vacuum cycles, enabling efficient regeneration of the adsorbent while maintaining high methane recovery [3].

The main advantages of PVSA include:

High methane purity: The methane (CH_4) concentration can be increased to **95%** or higher, making the upgraded biogas suitable for grid injection, vehicle fuel, and industrial energy applications [9].

High energy efficiency: The automated adsorption-desorption process minimizes energy consumption while maintaining high methane recovery and CO_2 removal efficiency.

Wide range of applications: PVSA technology enables the production of **bio-CNG** (compressed biomethane) and **bio-LNG** (liquefied biomethane), providing renewable alternatives to conventional natural gas.

Under the conditions of Uzbekistan, conventional biogas purification technologies are generally suitable for small- and medium-scale livestock farms, whereas **PVSA technology** is particularly appropriate for upgrading biogas generated from large municipal solid waste landfills, wastewater treatment plants, and high-capacity agricultural biogas facilities. Owing to its high methane recovery, low operating costs, and operational flexibility, PVSA represents one of the most promising technologies for future biomethane production in Uzbekistan [7] (Figure 1).

INTEGRATED SUSTAINABLE BIOGAS PRODUCTION AND UTILIZATION FRAMEWORK

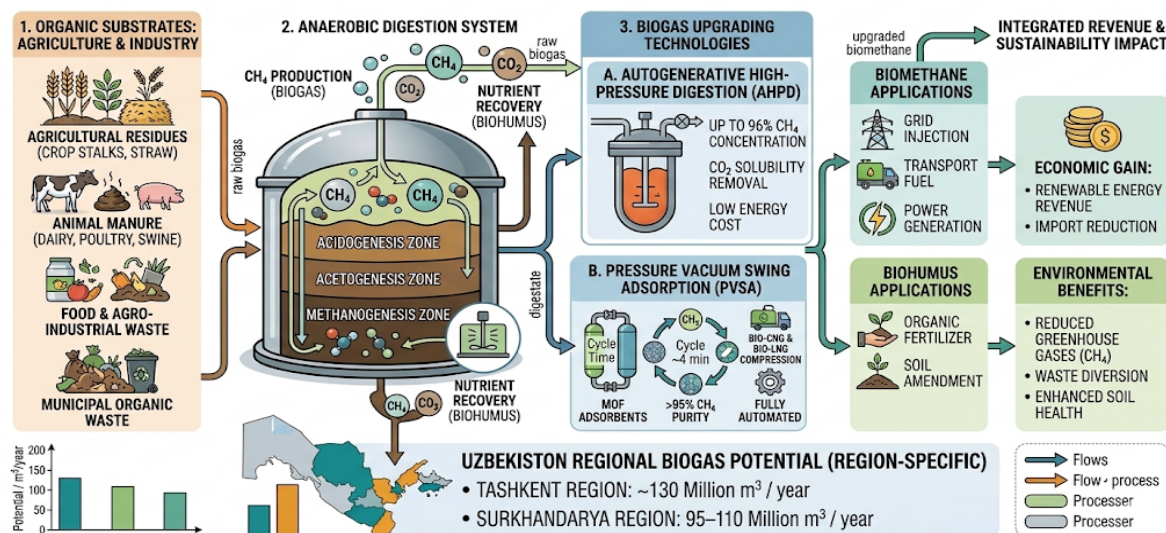
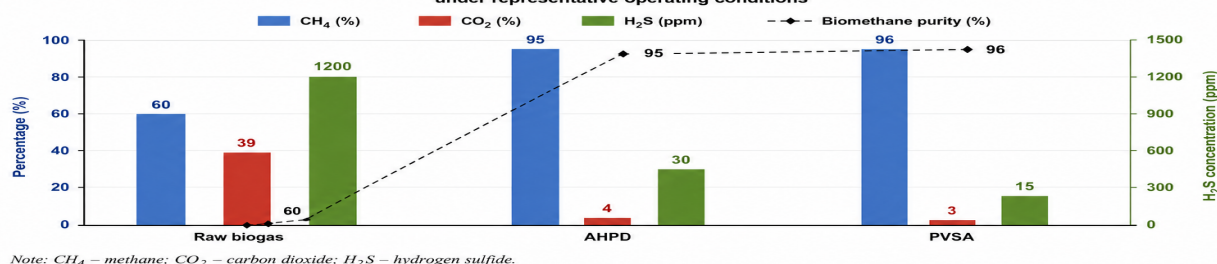


Figure 1. Statistical Metrics of Biogas Generation and Practical Implementation

Figure 1 illustrates the complete biogas production cycle and its potential practical implementation in Uzbekistan. Agricultural residues, livestock manure, food-processing waste, and municipal organic waste serve as the primary feedstocks for anaerobic digestion. During this biological process, organic substrates are converted into raw biogas and nutrient-rich digestate (biohumus). Subsequently, advanced upgrading technologies, including **Autogenerative High-Pressure Digestion (AHPD)** and **Pressure Vacuum Swing Adsorption (PVSA)**, are applied to increase methane purity by removing carbon dioxide and other impurities (Figure 2).

Figure 2. Comparative upgrading performance of raw biogas, AHPD and PVSA technologies under representative operating conditions



Note: CH₄ – methane; CO₂ – carbon dioxide; H₂S – hydrogen sulfide.

Table 2. Comparative performance of biogas upgrading technologies

Parameter	Raw biogas (before upgrading)	AHPD (High-pressure digestion)	PVSA (Pressure Vacuum Swing Adsorption)	Unit / Remarks
Methane (CH ₄)	60	95	96	% (vol.)
Carbon dioxide (CO ₂)	39	4	3	% (vol.)
Hydrogen sulfide (H ₂ S)	1200	30	15	ppm
Biomethane purity	–	95	96	%
Specific energy consumption	–	0.18	0.23	kWh/Nm ³ biomethane
Methane recovery	–	94	98	%
Operating pressure	Atmospheric	10–30	4–8	bar
Recommended application	Raw gas utilization	Medium-scale livestock farms	Large municipal and industrial biogas plants	–
Main advantage	Low cost, simple handling	Low energy demand, integrated digestion	High CO ₂ removal efficiency, high methane recovery	–

Figure 2. Comparative Upgrading Performance of Raw Biogas, AHPD, and PVSA Technologies under Representative Operating Conditions

The comparative results presented in Figure 2 demonstrate the effectiveness of advanced biogas upgrading technologies in improving biomethane quality. Raw biogas typically contains approximately **60% methane (CH₄)**, **39% carbon dioxide (CO₂)**, and around **1,200 ppm hydrogen sulfide (H₂S)**, making it unsuitable for direct injection into the natural gas grid. Following upgrading with the AHPD system, the methane concentration increases to approximately **95%**, while the CO₂ concentration decreases to about **4%**, and the H₂S concentration is reduced to nearly **30 ppm**. PVSA technology provides slightly higher purification efficiency, producing biomethane with approximately **96% methane**, **3% CO₂**, and about **15 ppm H₂S**.

These results indicate that both technologies satisfy the typical biomethane quality requirements for transportation fuel, industrial energy applications, and gas grid injection [11]. Compared with untreated biogas, the methane concentration increases by more than **35 percentage points**, while the concentrations of carbon dioxide and hydrogen sulfide are significantly reduced. This confirms that advanced upgrading technologies substantially

improve gas quality and support cleaner, more efficient renewable energy production in Uzbekistan.

The upgraded biomethane can be utilized for grid injection, electricity generation, transportation fuels (**bio-CNG** and **bio-LNG**), and industrial energy applications. In addition, digestate can be used as an organic fertilizer, contributing to sustainable agricultural production. The regional assessment indicates that **Tashkent Region** possesses the highest biogas production potential, followed by **Surkhandarya** and **Fergana Regions**. These findings demonstrate that Uzbekistan has considerable biomass resources capable of supporting the expansion of the national biomethane industry and strengthening the country's renewable energy sector (Table 2).

Table 2. Comparative Technical Performance Indicators of Raw Biogas, AHPD, and PVSA Upgrading Technologies

Parameter	Raw biogas (before upgrading)	AHPD (High-pressure digestion)	PVSA (Pressure Vacuum Swing Adsorption)	Unit / Remarks
Methane (CH ₄)	60	95	96	% (vol.)
Carbon dioxide (CO ₂)	39	4	3	% (vol.)
Hydrogen sulfide (H ₂ S)	1200	30	15	ppm
Biomethane purity	–	95	96	%
Specific energy consumption	–	0.18	0.23	kWh/Nm ³ biomethane
Methane recovery	–	94	98	%
Operating pressure	Atmospheric	10–30	4–8	bar
Recommended application	Raw gas utilization	Medium-scale livestock farms	Large municipal and industrial biogas plants	–
Main advantage	Low cost, simple handling	Low energy demand, integrated digestion	High CO ₂ removal efficiency, high methane recovery	–

Table 2 summarizes the principal technical performance indicators of the evaluated upgrading technologies. The comparison reveals that PVSA achieves the highest methane recovery (**98%**) and biomethane purity (**96%**), making it particularly suitable for large-scale municipal and industrial biogas facilities. In contrast, AHPD operates with lower specific energy consumption (**0.18 kWh/Nm³ biomethane**) because carbon dioxide separation occurs during the anaerobic digestion process under elevated pressure, thereby reducing additional upgrading requirements.

Although PVSA requires slightly higher energy consumption than AHPD, its superior methane recovery and purification efficiency provide greater overall biomethane production. Consequently, AHPD is recommended for medium-scale agricultural biogas plants, whereas PVSA represents the preferred option for centralized biomethane production systems with high gas throughput. The combined evaluation demonstrates that technology selection should be determined by plant capacity, feedstock availability, required biomethane quality, and economic feasibility.

Economic and Environmental Benefits of Biogas Technologies

The implementation of modern biogas technologies provides substantial economic, environmental, and social benefits. In addition to producing renewable energy, biogas systems improve waste management practices, reduce greenhouse gas emissions, and contribute to sustainable rural development. The integration of advanced upgrading technologies such as **AHPD** and **PVSA** further enhances biomethane quality and expands its commercial applications.

Economic Benefits

The economic advantages of biogas technologies can be summarized as follows:

Additional source of income: Livestock farms, agricultural enterprises, and food-processing industries can generate additional revenue by converting organic waste into biogas for on-site consumption or commercial sale. Excess biomethane can also be supplied to local energy networks or used as transportation fuel.

Production of high-quality biofertilizer: Anaerobic digestion produces nutrient-rich digestate (biohumus), which can partially replace synthetic fertilizers. The use of biohumus improves soil fertility, increases agricultural productivity, and reduces fertilizer expenditure.

Improved energy security: The utilization of locally available biomass resources reduces dependence on

imported fossil fuels, such as natural gas and coal, while strengthening national energy independence and resilience.

Creation of new employment opportunities: The development of the biogas sector creates new jobs in plant construction, operation, maintenance, biomass collection, transportation, and environmental monitoring, thereby supporting regional economic growth.

Environmental Benefits

Biogas technologies also provide significant environmental advantages:

Reduction of greenhouse gas emissions: The controlled anaerobic digestion of livestock manure and municipal organic waste prevents uncontrolled methane emissions from landfills and manure storage facilities, thereby reducing greenhouse gas emissions [13].

Sustainable waste management: Biogas production converts agricultural and municipal organic waste into valuable energy resources, minimizing environmental pollution and reducing the amount of waste disposed of in landfills.

Improvement of soil quality: The application of digestate as an organic fertilizer increases soil organic matter, improves soil structure, enhances water retention capacity, and decreases dependence on chemical fertilizers [10].

Contribution to climate change mitigation: The replacement of fossil fuels with biomethane contributes to reducing carbon emissions and supports Uzbekistan's transition toward a low-carbon and circular economy.

CONCLUSION AND RECOMMENDATIONS

This study evaluated the technological and practical potential of biogas production in Uzbekistan by integrating a regional biomass resource assessment with an analysis of advanced biogas upgrading technologies. The findings indicate that Uzbekistan possesses considerable quantities of agricultural residues, livestock manure, municipal organic waste, and agro-industrial by-products that can be converted into renewable energy through anaerobic digestion.

The regional analysis identified **Tashkent**, **Surkhandarya**, and **Fergana** as priority regions because of their high biomass availability and favorable conditions for large-scale biomethane production. The comparative assessment demonstrated that both **Autogenerative High-Pressure Digestion (AHPD)** and **Pressure Vacuum Swing Adsorption (PVSA)** can substantially improve biomethane quality by increasing methane concentration while reducing carbon dioxide and other impurities.

Among the evaluated technologies, PVSA appears particularly suitable for large municipal and industrial biogas facilities, whereas AHPD offers advantages for integrated digestion and upgrading processes with reduced external compression requirements. The results also confirm that the wider implementation of biomethane technologies can simultaneously improve energy security, reduce greenhouse gas emissions, enhance waste management, and support sustainable agricultural development through the utilization of digestate as an organic fertilizer.

Unlike previous studies, which primarily focused on individual upgrading technologies or general biomass resources, this research combines regional resource assessment with technology selection under the local conditions of Uzbekistan, thereby providing practical guidance for future biomethane development and investment planning.

To accelerate the development of the national biogas sector, the following recommendations are proposed:

Expand pilot biomethane projects beyond **Tashkent Region** to **Surkhandarya**, **Fergana**, and other regions with high biomass potential.

Promote the implementation of advanced upgrading technologies, particularly **AHPD** and **PVSA**, to improve biomethane purity and energy efficiency.

Strengthen the legislative and financial framework by introducing targeted subsidies, tax incentives, and investment support mechanisms for renewable gas projects [14].

Encourage cooperation among universities, research institutes, government agencies, and private investors to facilitate technology transfer and commercialization.

Future research should incorporate life-cycle assessment (**LCA**), techno-economic analysis (**TEA**), and optimization models to improve the long-term sustainability and economic feasibility of biomethane production in Uzbekistan.

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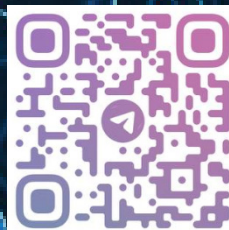
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