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05.01.00 – Axborot texnologiyalari, boshqaruv va kompyuter grafikasi
05.01.01 – Muhandislik geometriyasi va kompyuter grafikasi. Audio va video texnologiyalari
05.01.02 – Tizimli tahlil, boshqaruv va axborotni qayta ishlash
05.01.03 – Informatikaning nazariy asoslari
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05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
05.01.07 – Matematik modellashtirish
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05.02.00 – Mashinasozlik va mashinashunoslik
05.02.08 – Yer usti majmualari va uchish apparatlari
05.03.02 – Metrologiya va metrologiya ta'minoti
05.04.01 – Telekommunikasiya va kompyuter tizimlari, telekommunikasiya tarmoqlari va qurilmalari. Axborotlarni taqsimlash
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05.05.06 – Qayta tiklanadigan energiya turlari asosidagi energiya qurilmalari
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05.08.03 – Temir yo'l transportini ishlatish
05.08.06 – "G'ildirakli va gusenisali mashinalar va ularni ishlatish" (texnika fanlari)
05.09.01 – Qurilish konstruksiyalari, bino va inshootlar
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10.00.06 – Qiyosiy adabiyotshunoslik, chog'ishtirma tilshunoslik va tarjimashunoslik
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08.00.04 – Qishloq xo'jaligi iqtisodiyoti
08.00.05 – Xizmat ko'rsatish tarmoqlari iqtisodiyoti
08.00.06 – Ekonometrika va statistika
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08.00.09 – Jahon iqtisodiyoti
08.00.10 – Demografiya. Mehnat iqtisodiyoti
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08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 – Turizm va mehmonxona faoliyati

Ma'lumot uchun, OAK Rayosatining 2024-yil 28-avgustdagi 360/5-son qarori bilan "Dissertatsiyalar asosiy ilmiy natijalarini chop etishga tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga texnika va iqtisodiyot fanlari bo'yicha "Muhandislik va iqtisodiyot" jurnali ro'yxatga kiritilgan.

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MUNDARIJA • СОДЕРЖАНИЕ • CONTENTS

MUNDARIJA

RESEARCH AND DESIGN OF ANAEROBIC REACTORS FOR EFFECTIVE FERMENTATION OF AGRICULTURAL RESIDUE

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Abstract: This article presents the results of research into the development of efficient anaerobic digesters for processing dense agricultural residues, with a focus on halophytic plant biomass. It is demonstrated that optimizing the reactor design and process conditions can significantly increase biogas yields when processing mineral-rich plant substrates. Experiments have shown that processing halophytic plants (Karelinia caspia, Atriplex nitens, Glycyrrhiza glabra, and Suaeda paradoxa) under mesophilic conditions (35°C) results in a biogas yield of 350 ml per 1 g of dry substrate mass over 25 days. Microbial community analysis revealed the optimal ratio of methanogenic bacteria: 45-50% of the total methanogens are Methanosarcina, 30-35% are Methanosaeta, and 15-20% are Metanomicrobium. The developed technology ensures anaerobic digester productivity of 15-20 m³ of biogas per 1 m³ of reactor volume per day with a methane content of over 55%, guaranteeing a positive energy balance for the process. Microbial community analysis revealed the optimal ratio of methanogenic bacteria: 45-50% of the total methanogens are Methanosarcina, 30-35% are Methanosaeta, and 15-20% are Metanomicrobium. The developed technology ensures anaerobic digester productivity of 15-20 m³ of biogas per 1 m³ of reactor volume per day with a methane content of over 55%, guaranteeing a positive energy balance for the process.

Key words: halophyte raw materials, methanogenic bacteria, methane, biomethane, salsola, suaeda, climacoptera.

Annotatsiya: Ushbu maqolada galofit o‘simlik biomassasiga e’tibor qaratgan holda, zich qishloq xo‘jaligi qoldiqlarini qayta ishlash uchun samarali anaerob hazm qiluvchilarni ishlab chiqish bo‘yicha tadqiqotlar natijalari keltirilgan. Reaktor dizayni va jarayon sharoitlarini optimallashtirish minerallarga boy o‘simlik substratlarini qayta ishlashda biogaz hosildorligini sezilarli darajada oshirishi mumkinligi ko‘rsatilgan. Tajribalar shuni ko‘rsatdiki, galofit o‘simliklarni (Karelinia caspia, Atriplex nitens, Glycyrrhiza glabra va Suaeda paradoxa) mezofil sharoitda (35 °C) qayta ishlash 25 kun davomida 1 g quruq substrat massasiga 350 ml biogaz hosildorligiga olib keladi. Mikrobial jamoa tahlili metanogen bakteriyalarning optimal nisbatini aniqladi: umumiy metanogenlarning 45–50% Methanosarcina, 30–35% Methanosaeta va 15–20% Methanomicrobium. Ishlab chiqilgan texnologiya metan miqdori 55% dan yuqori bo‘lgan reaktor hajmining 1 m³ iga kuniga 15–20 m³ biogaz anaerob hazm qilish unumdorligini ta’minlaydi, bu jarayon uchun ijobiy energiya balansini kafolatlaydi.

Kalit so‘zlar: galofit xom ashyosi, metanogen bakteriyalar, metan, biometan, Salsola, Suaeda, Climacoptera.

Аннотация: В данной статье представлены результаты исследований по разработке эффективных анаэробных реакторов для переработки плотных сельскохозяйственных отходов с акцентом на биомассу галофитных растений. Показано, что оптимизация конструкции реактора и условий процесса может значительно увеличить выход биогаза при переработке богатых минералами растительных субстратов. Эксперименты показали, что переработка галофитных растений (Karelinia caspia, Atriplex nitens, Glycyrrhiza glabra и Suaeda paradoxa) в мезофильных условиях (35°C) приводит к выходу биогаза 350 мл на 1 г сухой массы субстрата за 25 дней. Анализ микробного сообщества выявил оптимальное соотношение метаногенных бактерий: 45-50% от общего числа метаногенов составляют Methanosarcina, 30-35% - Methanosaeta и 15-20% - Methanomicrobium. Разработанная технология обеспечивает производительность анаэробного реактора 15-20 м³ биогаза на 1 м³ объема реактора в сутки с содержанием метана более 55%, гарантируя положительный энергетический баланс процесса.

Ключевые слова: галофитное сырье, метаногенные бактерии, метан, биометан, сальсола, суаэда, климакоптера.

INTRODUCTION

In an era of worsening global energy crisis and intensifying climate change, the search for and implementation of environmentally friendly, renewable energy sources is becoming a priority for the sustainable development of the global agro-industrial complex [1]. These processes are of particular strategic importance for regions with arid and semi-arid climates, including the Republic of Uzbekistan, where the shortage of traditional energy resources in remote rural areas is compounded by the need to dispose of colossal volumes of organic waste[2]. Biogas production by anaerobic digestion of agricultural and plant residues not only diversifies the local energy

balance by producing high-calorie biomethane, but also minimizes uncontrolled greenhouse gas emissions generated by natural decay or burning of biomass in fields[3].

REVIEW OF LITERATURE ON THE SUBJECT

The phytomass of halophytic plants is being promoted as an innovative and environmentally sound raw material base for biogas plants. In the context of progressive secondary soil salinization and the desiccation of the Aral Sea, vast areas of marginal land in Central Asia are being withdrawn from traditional agricultural use [4]. These territories are naturally colonized by salt-tolerant plants of the Salsola, Suaeda, and Climacoptera genera, which form a significant annual biomass that does not compete with food crops for arable land and fresh water [5]. The specific chemical composition of halophytes is that, during their life cycle, their cells accumulate high concentrations of mineral components, including potassium, sodium, magnesium, and calcium salts, as well as a wide range of essential microelements such as nickel, cobalt, iron, and selenium [6].

The presence of these mineral complexes within the cell sap of halophytic plants is crucial for intensifying the metabolism of methanogenic microorganisms. During anaerobic digestion, these ions are released into the liquid phase of the substrate and begin to act as natural cofactors for the key enzymatic systems of methanogens responsible for the final stages of biomethane synthesis [7]. In particular, nickel and cobalt are part of the essential coenzyme F-430, which catalyzes the reaction of methyl group reduction to gas, while iron and selenium activate hydrogenases and formate dehydrogenases of the methanogenic consortium [8]. Thus, the controlled introduction of halophytes into the fermentation mixture not only enriches the reaction medium with available carbon, but also eliminates the microelement deficiency typical of mono-fermentation of clean livestock manure, elevating the process to a qualitatively new level of stability and productivity [9].

RESEARCH METHODOLOGY

The object of this study is specific groups of methanogenic archaea, which are key microorganisms in the final stage of anaerobic decomposition of organic matter. This study examined three morphologically and physiologically distinct groups of methanogens in detail [10].

The subject of the study is specific groups of plant substrates that differ in morpho-anatomical characteristics, biochemical composition and ecological association (Karelinia caspia, Atriplex nitens Schkuhr) [11].

Additional plant substrates included gardening and vegetable growing waste of various botanical origins: pomace of pome fruits (apple, pear) and stone fruits (plum, apricot), tops of root crops (carrot, beet) and waste from the processing of melons (watermelon, melon), characterized by variable content of easily hydrolyzed carbohydrates (15-45% dry mass) and different levels of mineralization [12].

A comprehensive study of these substrates made it possible to evaluate the influence of the species characteristics of plant materials, the degree of its mineralization and biochemical composition on the efficiency of anaerobic fermentation and the activity of various groups of methanogenic microorganisms under mesophilic temperature conditions [13].

ANALYSIS AND RESULTS

Experimental studies of the kinetics of anaerobic digestion of the developed substrates under mesophilic conditions at 35°C demonstrated a pronounced dependence of biogas yield on the botanical origin and mineralization level of the plant material. When cultivating a microbial consortium on pure halophytic substrates represented by the phytomass of Karelinia caspia, Atriplex nitens, Glycyrrhiza glabra, and Suaeda paradoxa, gas production dynamics were characterized by the absence of a pronounced lag phase. This is due to the high content of water-soluble mineral components in the cell sap of these plants, which act as natural catalysts for enzymatic processes.

Over 25 days of continuous incubation, the average specific biogas yield for the studied halophyte group was 348 ml/1 g of substrate dry weight. The dynamics of daily gas generation recorded two distinct peaks: the first on day 3 of exposure, associated with the rapid bioconversion of easily hydrolyzable sugars and pectin substances, and the second on days 11-12, caused by the decomposition of the hemicellulose fraction.

When additional plant substrates containing gardening and vegetable waste (apple and pear pulp, carrot and beet tops) were added to the reaction mixture, the hydrolysis rate increased significantly. Due to the high content of readily hydrolyzable carbohydrates, ranging from 15 to 45% of the dry mass, the medium rapidly acidified within the first 48 hours to a pH of 5.8. However, the concomitant presence of mineral-rich biomass of Suaeda paradoxa and Atriplex nitens, which possess high internal buffering capacity due to calcium and

magnesium salts, allowed the pH to be stabilized in the optimal range of 6.8 to 7.4 without the forced addition of alkaline reagents (Figure 1).

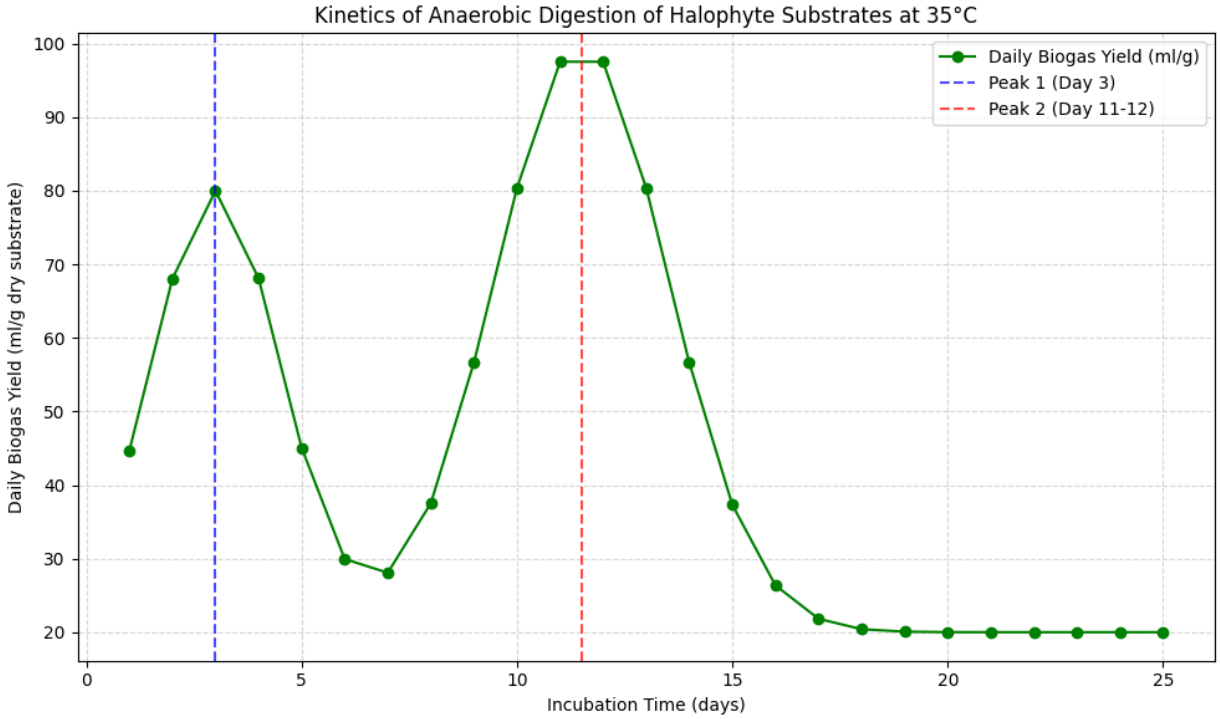

Figure 1. Kinetics of Anaerobic of Halophyte Substrates at 35^0 C[1]

Monitoring the qualitative composition of the gas phase using a chromatographic system showed that methane concentrations consistently remained above 55% throughout the entire period of active methanogenesis, reaching a maximum of 62% by day 18 of the experiment. The final operating productivity of the modified anaerobic reactors was recorded at 15 to 20 m³ of biogas per 1 m³ of reactor working volume per day, confirming the high efficiency of the proposed design solutions and process modes.

For a clear comparison of the conversion efficiencies of the various studied phytosubstrates and their compositions with vegetable waste, the results are summarized in Table 1 (Table 1).

Table 1. Kinetic and bioenergetic parameters of anaerobic digestion of plant substrates (t = 35°C, digestion period = 25 days)[2]

Name of the plant substrate (or composition)	Total biogas yield, ml/g dry mass	Average methane content (CH_4), %	Specific productivity, m³ biogas / m³ reactor per day
Mono-substrate Karelinia caspia	342±pm 12	56.2	15.4
Mono-substrate Atriplex nitens	351 ±pm 10	57.8	16.8
Halophyte mixture (Glycyrrhiza glabra + Suaeda paradoxa)	355 ±pm 15	58.1	17.2
Composition: Halophytes (50%) + Pome fruit pomace (50%)	382 ±pm 18	55.4	19.5
Composition: Halophytes (50%) + Root crop tops (50%)	368 ±pm 14	56.0	18.1

High specific biomethane yields and digestion stability are explained by analyzing the structural and functional organization of the archaeal microbial consortium. Molecular genetic and microbiological analyses revealed a strictly balanced ratio of the main trophic groups of methanogens. Representatives of the genus Methanosarcina dominated the bioreactor, accounting for 45 to 50% of the total methanogenic archaeal pool.

1 Source: Compiled by the author.
2 Source: Compiled by the author.

The ability of Methanosarcina microorganisms to utilize various metabolic pathways (both acetoclastic and hydrogenotrophic) ensured the system's high flexibility and resistance to fluctuations in volatile fatty acid concentrations during rapid loading of melon and horticultural waste.

The proportion of obligate acetoclastics of the genus Methanosaeta fluctuated between 30 and 35%. These archaea have a high affinity for acetate and efficiently utilize it even at low concentrations, preventing a critical drop in acidity and maintaining thermodynamic equilibrium during the final stage of fermentation. The hydrogenotrophic group, represented primarily by the genus Methanomicrobium, remained stable at 15-20%. Methanogens of this type rapidly bound free hydrogen and carbon dioxide, preventing hydrogen from inhibiting accompanying acetogenic bacteria.

This synergistic microbiological profile was formed directly due to the specific mineralization of halophytic biomass. Microelements (cobalt, nickel, and iron) released during the destruction of Karelinia caspia and Atriplex nitens cells served as readily available building blocks for the synthesis of archaeal metalloenzymes. Specifically, cobalt intensified the activity of the coenzyme F-430 in Methanosarcina, reducing the time it takes to generate microbial biomass and shifting the kinetic equilibrium toward methane formation. The positive energy balance recorded during pilot tests demonstrates that the amount of energy accumulated in the resulting biomethane significantly exceeds the biogas plant's internal process requirements for maintaining a mesophilic temperature regime and mixing, opening up broad prospects for decentralized implementation of the technology.

CONCLUSIONS AND SUGGESTIONS

Based on comprehensive research, the effectiveness of using halophyte plant phytomass (Karelinia caspia, Atriplex nitens, Glycyrrhiza glabra, Suaeda paradoxa) both individually and in combination with carbohydrate-containing gardening and vegetable waste for the stable production of biomethane has been scientifically substantiated and experimentally verified.

It has been established that optimizing anaerobic conditions in a mesophilic regime at 35°C ensures a specific biogas yield of 30-50 ml/g of substrate dry weight over a 23-25-day fermentation cycle. This technological benefit is determined by the formation of a stable microbial consortium, in which key positions are held by the genera Methanosarcina (45-50%) and Methanosaeta (30-35%), whose enzymatic activity is catalyzed by endogenous microelements in the halophytic feedstock.

The developed biotechnology and the parameters of the modernized bioreactors ensure stable daily productivity of 15-20 m³ of gas per 1 m³ of reactor space at methane concentrations above 55%. The achieved stable positive energy balance allows this technology to be recommended for widespread implementation in arid and saline regions of the Republic of Uzbekistan, solving a dual problem: generating autonomous energy sources and environmentally safe disposal of large-tonnage plant waste from the agro-industrial complex.

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