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Article

Organizational and Economic Mechanisms of Organization of Agro-Industrial Clusters

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Abstract: The article discusses the organizational and economic mechanisms for creating agro-industrial clusters specializing in the processing of organic waste into biogas, compost, thermal energy and other commercial products. A comparative analysis of three clusters was carried out - in the USA (California, Iowa), Europe (Germany, the Netherlands, Denmark) and Uzbekistan. The research uses methods of structural analysis, comparative institutional analysis, and case-study methodology. It has been established that the effectiveness of biogas clusters depends not only on technological parameters, but also, first of all, on the quality of institutional design: the availability of public-private partnerships, stimulating regulatory frameworks and integration mechanisms throughout the value chain. Specific organizational models adapted to the conditions of the Uzbek agro-industrial complex are proposed. The results show that the potential annual production of biogas from agricultural and municipal organic waste in Uzbekistan exceeds 2.5 billion US dollars. m^3, which corresponds to 3.1 billion. kWh of electricity.

Keywords: agro-industrial cluster, biogas, organic waste recycling, public-private partnership, Uzbekistan, green economy, value chain, bioenergy.

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1. Introduction

The global transition to a "green" economy has actualized the task of closing resource cycles in agro-industrial production. More than 1.3 billion tons of food and agricultural organic waste are generated annually in the world, which is equivalent to the loss of about 8-10% of the world's energy reserves and the formation of significant amounts of greenhouse gases. The processing of these wastes into biogas, compost, biochar and carbon dioxide for industrial needs is one of the most promising mechanisms for the simultaneous solution of environmental, energy and economic problems [1].

An agro-industrial cluster as an organizational form unites technologically interconnected enterprises, scientific institutions and government agencies within a single value chain. As for bioenergy specialization, such a cluster includes producers of raw materials (farmers, municipal services), processors (biogas and composting plants), end users (power plants, agricultural enterprises, chemical industry) and institutional participants (banks, insurers, regulatory authorities) [2, 3]. The relevance of the study is determined by the fact that Uzbekistan, having a huge potential in the field of organic waste (more than 6.2 million tons per year from livestock production alone), has not yet formed a systematic cluster infrastructure of a biogas profile. A comparative analysis of the experience of the USA and Europe allows us to identify universal mechanisms and adapt them to national specifics.

The purpose of the study is to develop a conceptual model of the organizational and economic mechanism of the agro-industrial bioenergy cluster based on a comparative analysis of international practice and an assessment of the potential of Uzbekistan.

Research objectives: (1) to systematize the theoretical foundations of the cluster approach in relation to bioenergy processing of organic waste; (2) to conduct a comparative analysis of the cluster models of the USA, the EU and Uzbekistan; (3) to develop and justify an organizational and economic model for these conditions from Uzbekistan.

2. Methodology

The methodological basis of the research is a set of general scientific and special methods. The theoretical basis consists of M. Porter's work on cluster competitiveness [4], the concept of the "triple helix" by J. Itzkowitz [5], as well as the theory of the value chain by M. Porter and G. Gereffi [6].

In the empirical part (a), the case study method was used to analyze three regional cluster models; (b) comparative institutional analysis of regulatory and organizational mechanisms; (c) structural and functional analysis of technological chains of organic waste processing; (d) economic and mathematical modeling of biogas potential. production in Uzbekistan.

Information base: official statistics from the US Department of Agriculture, Eurostat, and the Agency for Statistics of the Republic of Uzbekistan; reports from the International Renewable Energy Agency (IRENA); ScienceDirect and Scopus databases; regulatory acts of the Republic of Uzbekistan (Decree No. UP-205 dated 12/12/2023, Resolution No. UP-52 dated 12/15/2021) [7].

3. Literature review

The conceptual basis of cluster theory was laid by Alfred Marshall with the idea of "localized industrial specialization." The theory of industrial clusters was systematically developed in the works of Michael Porter, who in 1994 substantiated the thesis that the spatial concentration of interconnected firms and institutions increases the competitiveness of a region through innovation and productivity [4, 8].

Agro-industrial clusters are considered by modern researchers as a new organizational model that has become the driving force behind the growth of agriculture. Based on panel data on 1,467 counties in China for 2013-2020, the two-stage MNC method showed that agro-industrial clusters significantly increase the total factor productivity (TFP) of agriculture, and the effect is more pronounced in regions with a high level of human capital [9].

As for the bioenergy specialization of clusters, the concept of "industrial symbiosis" acquires a special role, according to which waste from one cluster member becomes a resource for another. This concept was successfully implemented in the "Eco-Industrial Park" Kalundborg (Denmark), recognized as a benchmark for the entire world practice [10].

In the Uzbek scientific literature, the organizational and economic mechanism of an agro-industrial cluster is defined as a self-organizing system of economic entities with their inherent management mechanisms and regulatory state economic institutions [11]. Research shows that the "triple helix" model: state -academy - production is critically important for agricultural clusters in Uzbekistan [12].

4. Results

The technological chain of processing organic waste into biogas and other products. The processing of organic waste in an agro-industrial cluster is a multi-stage process with several groups of end products. The basic technological chain includes five consecutive stages (Table 1).

Table 1. Technological chain of organic waste processing in an agro-industrial biogas cluster

Stage	Description	Products / Output
1. Collection and sorting	Separate collection of organic MSW, manure, and plant residues	Fractions by type and moisture cor
2. Pre-treatment	Grinding, homogenization, substrate heating to 35–55°C	Homogeneous slurry
3. Anaerobic digestion	Methane fermentation in bioreactor (15–30 days); T = 35–55°C	Biogas (55–75% CH_4); digestate
4. Biogas utilization	Cogeneration: ICE/turbine → electricity + heat; or upgrading to biomethane	Electricity (2–3 kWh/m³); biomethane
5. Digestate processing	Separation: liquid fraction → liquid fertilizer; solid → compost / biochar	Compost, bio-fertilizers, biochar

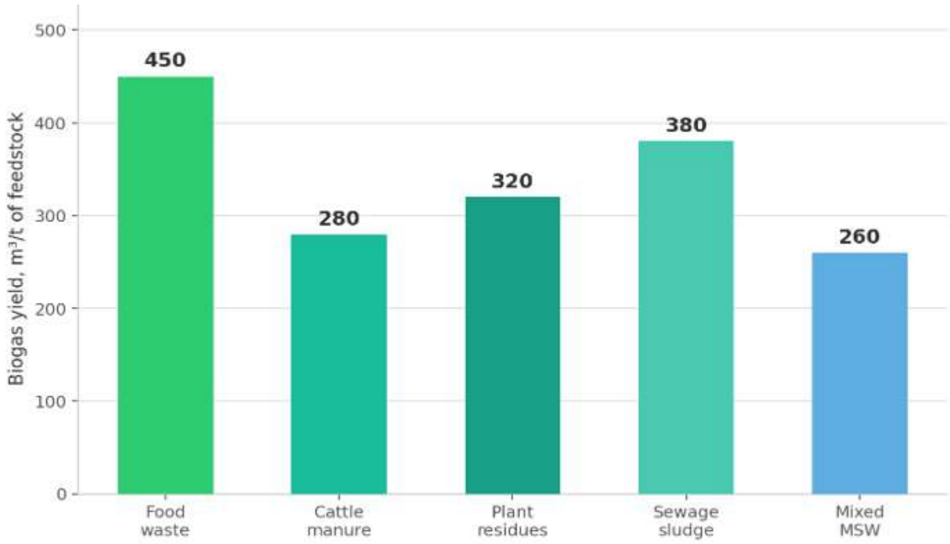


Figure 1. Biogas Yield from Various Types of Organic Feedstocks (m³/t)

As can be seen from Figure 1, the maximum biogas production is provided by food waste (450 m3/t), which is due to the high content of easily digestible carbohydrates and proteins. Cattle manure, although it has a lower specific productivity (280 m3/t), is the most common type of raw material in agro-industrial regions [1, 13].

Case 1: Biogas agro clusters in the USA (California, Iowa).

The United States has one of the most developed institutional support systems for the biogas industry. According to the American Biogas Council, by 2023, there were more than 2,200 biogas plants operating in the country with a total capacity of about 3.5 GW, annually generating more than 50 billion kWh of electricity [13].

- Key organizational and economic mechanisms of American biogas clusters:
- Government incentives: federal Investment Tax Credit (ITC, 30% of capital investments), the US Department of Agriculture's Rural Energy for America (REAP) program, farm subsidies [14].
- The market mechanism of "green loans" (renewable identification numbers - RINS): biomethane producers sell RINS to oil companies to fulfill obligations under the

- renewable fuel standard (RFS), providing additional income in the amount of 0.5 - 1.2 USD/m3 of biogas [15].
- Vertical cluster integration: The Iowa Manure Management Initiative Group unites more than 500 pig farms into a single network of collective manure processing with a centralized biogas plant with a capacity of 12 MW.
- Digital management platforms: IoT-monitoring of gas composition, temperature and pH in real time; blockchain-tracking of RINs certificates.

Table 2. Economic performance indicators of biogas agro-industrial clusters in the USA (2022-2023)

Indicator	California (organic MSW)	Iowa (swine manure)
Feedstock volume, t/year	320	480
Biogas production, m³/year	48,0	64,5
Power generation capacity, MW	6,4	12,0
Compost output, t/year	85	140
Cluster revenue, million USD/year	28,4	41,7
Payback period, years	6–8	7–9
Number of direct jobs	120	190
CO_2-eq. emission reduction, 1000 t/year	68	105

Case 2: Biogas agro-clusters in Europe (Germany, the Netherlands, Denmark)

The European Union holds a leading position in global biogas production: by 2023, the total capacity of installations reached 22 GW, and biomethane production increased by 40% over the period 2019-2023 [16]. The main difference between the European model is the use of biomethane (purified biogas) with subsequent injection into a common gas network.

The German model (BioenergieDorf - "village of bioenergy") provides for the creation of cooperative clusters at the level of rural communities. According to BMEL, by 2023, there were about 9,500 biogas plants operating in the country with a total electric capacity of 5.8 GW. The efficiency of the German model is ensured by the EEG law (Erneuerbare-Energien-Gesetz), a system of guaranteed tariffs for "green" electricity and biomethane [17].

The Danish industrial symbiosis model (Kalundborg Symbiosis) demonstrates the most advanced cluster organization option: biogas plant waste (heat, CO_2, digestate) is completely disposed of by neighboring enterprises - a greenhouse complex, a pharmaceutical plant and a fish farm. The annual savings amount to about 19 million euros and prevent

Criterion	Germany	Netherlands	Denmark
Number of biogas plants	~9 500	~450	~170
Total capacity, GW	5,8	0,38	0,21
Share in national RES generation	9,4%	4,2%	3,8%
Main cluster product	Electricity	Biomethane to grid	Heat + CO_2
Subsidy mechanism	EEG tariff	SDE+ subsidy	Tax deduction
PPP model	Community cooperatives	PPP concessions	Industrial symbiosis

emissions of 275,000 tons of CO_2 [10, 18]. **Table 3.** Comparative overview of biogas clusters in the EU

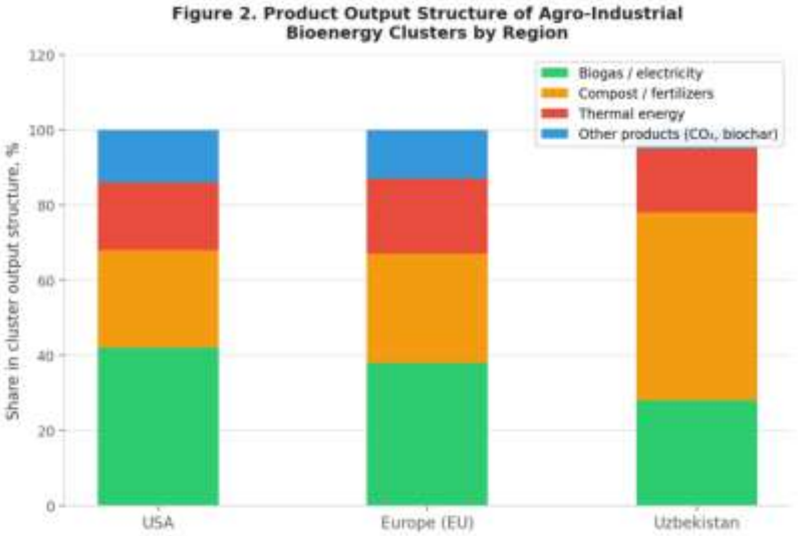


Figure 2. The structure of the product output of agro-industrial bioenergy clusters by region

Case 3: Capacity and institutional arrangements of Uzbekistan

Uzbekistan has significant potential for the development of biogas agro-industrial clusters. According to the Agency of the Republic of Uzbekistan for Statistics, in 2023, the number of cattle amounted to about 12.5 million heads, pigs and sheep — more than 21 million heads, which forms an annual manure yield of about 60 million tons. In addition, about 4.3 million tons of plant residues (cotton, rice, wheat) and about 2.1 million tons of household organic waste are generated in cities [19].

The institutional framework for the development of clusters in the country was laid by Presidential Decree No. UP-52 dated 12/15/2021 and Decree No. UP-205 dated 12/12/2023, which provide for: the introduction of IFRS in clusters, independent external audit, the inclusion of requirements for innovative cooperation in licensing procedures, as well as as a mechanism for taking into account the needs of agro-clusters when forming research topics [7].

Table 4. The potential of biogas production from organic waste from the agro-industrial complex of Uzbekistan

Region	Organic waste volume, thousand t/year	Potential biogas, million m³/year	Electricity, million kWh/year	Compost, thousand t/year
Fergana Valley	1 850	462,5	555	820
Tashkent region	1 420	355,0	426	630
Samarkand region	1 100	275,0	330	488
Kashkadarya region	980	245,0	294	435
Andijan region	860	215,0	258	382
Other regions	1 990	497,5	597	884
TOTAL	8 200	2 050,0	2 460	3 639

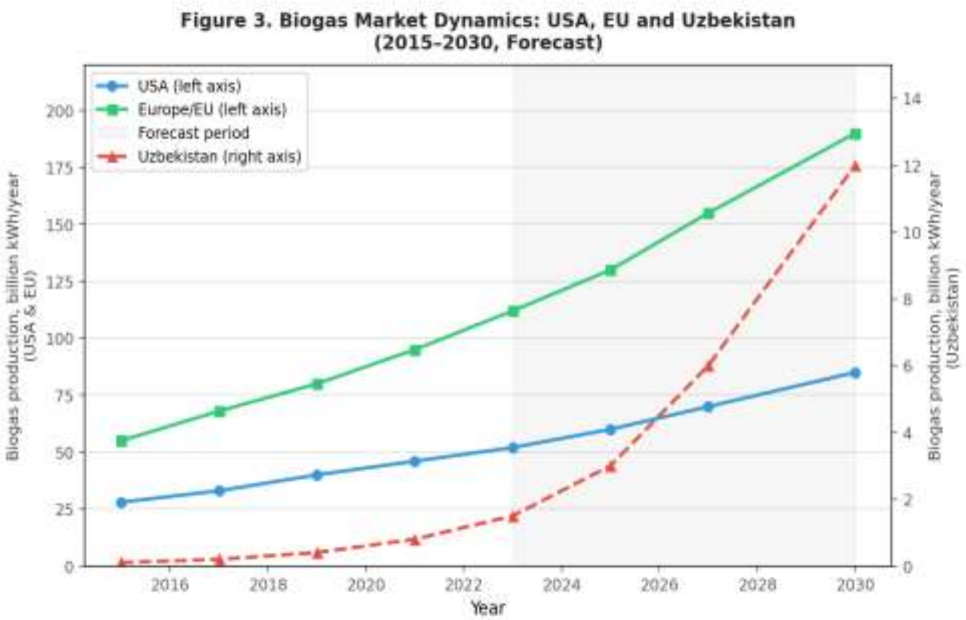
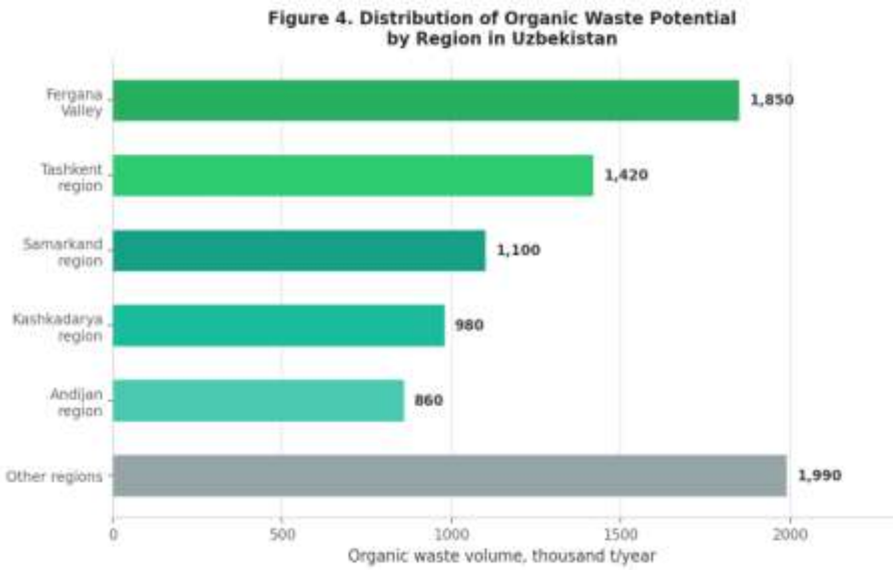


Figure 3. Biogas Market Dynamics: USA, EU and Uzbekistan (2015–2030, Forecast)

Figure 4. Biogas production potential from agricultural organic waste in Uzbekistan



3.5 Comparative Analysis of Organizational and Economic Mechanisms across Three Regions

Table 5. Comparative Analysis of Organizational and Economic Mechanisms of Biogas Agro-Industrial Clusters

Mechanism / Criterion	USA	Europe (EU)	Uzbekistan
Regulatory framework	EPA, RFS, Farm Bill	EEG, RED II, EU Biogas Strategy 2030	ПП-52/2021, 205/2023
PPP model	Concessions, PPP	Community cooperatives, PPP	Cluster system 2017
Financial instruments	ITC (30%), REAP grants	EEG feed-in tariff, SDE+, зелёные облигации	Preferential loans Uzpromstroybank, subsidies
Key product	Electricity + RINs	Biomethane to gas grid	Electricity + compos
Cluster maturity level	High (stage 4)	High (stage 4-5)	Early (stage 2)
Digitalization	IoT, blockchain	Industry 4.0, digital twin	Pilot projects
Value chain coverage	Full	Full (symbiosis)	Partial (farm processing)

5. Discussion

Conceptual model of bioenergy agro-industrial cluster for Uzbekistan. Based on a comparative analysis of three regional models, we proposed a conceptual organizational and economic model of a bioenergy agro-industrial cluster for the conditions of Uzbekistan. The model is based on the concept of a “triple helix” and includes three levels of interaction between participants [5, 11]:

Table 6. Three-level organizational model of Uzbekistan bioenergy agro-industrial cluster

Level	Partici pants	Functions and Mechanisms
I - Production	Farms, agro-holdings, municipal solid waste management services	Supply of organic feedstock, waste sorting, logistics to the biogas plant
II - Processing	Biogas plants (CBS), composting facilities, bio-fertilizer production enterprises	Anaerobic digestion, cogeneration, digestate separation, production of bio-fertilizers and biochar
III - Market-Institutional	Energy supply companies, agricultural enterprises (fertilizer consumers), banks, government agencies, universities (TSAU, TashSTU)	Sales of electricity, heat, and compost; provision of preferential loans; R&D; personnel training; certification

Financial and economic justification of the pilot cluster

A biogas agro-industrial cluster in the Ferghana Valley (Andijan/Namangan region) as the densest agricultural region of the country. The technical and economic parameters are presented in Table 7.

Table 7. Technical and economic indicators of the pilot biogas agro-industrial cluster (Fergana Valley, Uzbekistan)

Parameter	Value
Volume of processed waste, thousand t/year	250 (cattle manure + food waste)
Installed capacity of biogas plant, MW	4,0
Annual electricity production, million kWh	28,0
Annual heat energy production, thousand Gcal	38,5
Compost and bio-fertilizer output, thousand t/year	60
Capital expenditures (CAPEX), million USD	12,5–15,0
Operating expenses (OPEX), million USD/year	1,8–2,2
Annual cluster revenue, million USD	6,4–7,8
Payback period (without subsidies), years	9–12
Payback period (with 30% subsidies), years	6–8
Internal rate of return (IRR), %	14–18
Net present value (NPV, 10 years), million USD	8,2–11,6
Direct jobs	85–110
CO_2-eq. emission reduction, thousand t/yearод	48–62

A number of system banks have appeared on the way to creating an innovative biogas agro-industrial complex in Uzbekistan. The main barriers and proposed mechanisms for overcoming them are presented in Table 8.

Table 8. Barriers and mechanisms for overcoming them in the creation of biogas agro-industrial clusters in Uzbekistan

Barrier Type	Description of problem	Recommended Mechanism
Institutional	Absence of a dedicated law on biogas and organic waste management	Adoption of a Bioenergy modeled on the German introduction of guaranteed fe tariffs
Financial	High cost of capital; limited SME access to green financing	Establishment of a green invest guarantee fund with EBRD and participation; green bonds
Technological	Shortage of domestic equipment; dependence on imported biogas reactors	Technology transfer through with German (Envitec) and Ch (CIFOR) manufacturers
Human Resources	Shortage of engineers in anaerobic digestion and bioenergy	Introduction of specia programs at TSTU and T internships in Europe under Horizon EU program
Market	Underdeveloped organic fertilizer market; low prices for conventional fertilizers	Subsidization of bio-fertilizer mandatory quota for cluster me farmers

6. Conclusion

The conducted research allows us to formulate the following main conclusions:

Firstly, the processing of organic waste into biogas, compost and other products within the framework of agro-industrial clusters is an economically efficient and environmentally sound direction for the development of agriculture. Comparative analysis has shown that with proper institutional support, the IRR of biogas clusters is 14-22%, and the payback period is 6-9 years [1, 13, 17].

Secondly, the key success factor is institutional design: the availability of special legislation (similar to the EEG in Germany or the RFS in the USA), PPP mechanisms and the diversification of the cluster's product basket (electricity + heat + compost + CO_2). The most perfect organizational form is the industrial symbiotic model implemented in Denmark [10, 18].

Thirdly, Uzbekistan has a significant potential for biogas production (estimated output is over 2,050 million m3/year of biogas), however, the realization of this potential requires a comprehensive organizational and economic mechanism: a special industry law, a financial guarantee fund, technology transfer and personnel training [7, 19].

The proposed three - level cluster model (production - processing - market-institutional levels) ensures the closure of resource cycles within a single value chain and allows attracting international financing through the mechanisms of "green" climate finance (GCF, GEF). The priority pilot regions for the implementation of the proposed model are the Ferghana Valley and the Tashkent region, as the densest areas in terms of agricultural production concentration.

The practical significance of the work lies in the fact that the proposed organizational models and financial and economic calculations can be used by the Ministry of Agriculture of the Republic of Uzbekistan, the Ministry of Energy of the Republic of Uzbekistan, as well as potential investors in the development of feasibility studies for biogas agro-industrial clusters

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