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## BIOENERGY WASTE RECYCLING: MODELLING OF DEVELOPMENTAL TRENDS

**Purpose.** Modelling environmentally safe bioenergy trends based on national and international patent databases and scientific databases.

**Methods.** Bibliometric method of analysis using the Scopus database and patent databases, modeling methods using a special visualization software package.

**Results.** An analytical diagram based on the review of patent databases was developed, as well as a model for visualization of interrelationships between clusters of bioenergy development trends as a complex solution for environmental protection. Thus, 4 clusters were formed based on data from the Scopus database using VOSviewer software: 1) cluster (red) reveals the environmental problems of changing the direction of implementation of stationary energy sources with the development of bioenergy potential, and the creation of strategies for this development at the level of regions; 2) cluster (yellow) covers the process of restoration of ecological systems, in particular forests and reduction of CO<sub>2</sub> emissions from bioenergy; 3) cluster (green) covers the production and use of different types of fuel and energy produced by the introduction and improvement of bioenergy technologies; 4) cluster (blue) covers the impact of bioenergy technologies on environmental restoration and purification and reduction of damage from anthropogenic impact.

**Conclusions.** The analysis of patent databases with cluster visualization based on a bibliometric approach allowed to identify the most promising areas of research in the field of bioenergy solutions development. Further research will be focused on the development of a lab bench for biogenic gas production with the possibility of complex processing of secondary raw materials and obtaining environmentally safe digestates.

**KEYWORDS:** bibliometric approach, cluster visualization, bioenergy, technological solutions, modeling, environmental protection

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## БІОЕНЕРГЕТИЧНА УТИЛІЗАЦІЯ ВІДХОДІВ: МОДЕЛЮВАННЯ НАПРЯМКІВ РОЗВИТКУ

**Мета.** Моделювання екологічно безпечних напрямів розвитку біоенергетики з використанням вітчизняних, зарубіжних патентних та наукометричних баз даних.

**Методи.** Бібліометричний метод аналізу з використанням наукометричної бази Scopus і патентних баз даних, методи моделювання з використанням спеціального програмного пакета візуалізації.

**Результати.** Розроблена аналітична діаграма на основі огляду патентних баз даних, а також сформована модель візуалізації взаємозв'язків між кластерами напрямків розвитку біоенергетики як комплексного рішення для захисту довкілля. Сформовано 4 кластери за даними БД Scopus з використанням програмного забезпечення VOSviewer: 1) кластер (червоний) розкриває екологічну проблематику зміни напрямку реалізації стаціонарних джерел отримання енергії з розвитком потенціалу біоенергетики, і створення стратегій розвитку на регіональному рівні; 2) кластер (жовтий) охоплює процес відновлення екологічних систем зокрема лісів та зменшення викидів CO<sub>2</sub> при використанні біоенергетики; 3) кластер (зелений) охоплює виробництво і застосування різних видів палива і енергії, одержуваних шляхом введення та покращення біоенергетичних технологій; 4) кластер (блакитний) охоплює вплив біоенергетичних технологій на відновлення та очищення навколишнього середовища і зменшення шкоди від антропогенного впливу.

**Висновки.** Аналіз патентних баз даних з кластерної візуалізацією на основі бібліометричного підходу дозволив виділити найбільш перспективні напрямки досліджень в області розробки біоенергетичних рішень. Подальші дослідження будуть спрямовані на розробку лабораторного стенду виробництва біогенного газу з можливістю комплексної переробки вторинної сировини і отриманням екологічно безпечних дигестатів.

**КЛЮЧОВІ СЛОВА:** бібліометричний підхід, кластерна візуалізація, біоенергетика, технологічні рішення, моделювання, захист навколишнього середовища

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## **БИОЭНЕРГЕТИЧЕСКАЯ УТИЛИЗАЦИЯ ОТХОДОВ: МОДЕЛИРОВАНИЕ НАПРАВЛЕНИЙ РАЗВИТИЯ**

**Цель.** Моделирование экологически безопасных направлений развития биоэнергетики с использованием отечественных, зарубежных патентных и наукометрических баз данных.

**Методы.** Библиометрический метод анализа с использованием наукометрической базы Scopus и патентных баз данных, методы моделирования с использованием специального программного пакета визуализации.

**Результаты.** Разработана аналитическая диаграмма на основе обзора патентных баз данных, а также сформирована модель визуализации взаимосвязей между кластерами направлений развития биоэнергетики как комплексного решения для защиты окружающей среды. Так, было сформировано 4 кластера по данным БД Scopus с использованием программного обеспечения VOSviewer: 1) кластер (красный) раскрывает экологическую проблематику изменения направления реализации стационарных источников получения энергии с развитием потенциала биоэнергетики, и создание стратегий этого развития на уровне регионов; 2) кластер (желтый) охватывает процесс восстановления экологических систем в частности лесов и уменьшению выбросов CO<sub>2</sub> при использовании биоэнергетики; 3) кластер (зеленый) охватывает производство и применение различных видов топлива и энергии, получаемых путем введения и улучшение биоэнергетических технологий; 4) кластер (голубой) охватывает влиянием биоэнергетических технологий на восстановление и очистку окружающей среды и уменьшения ущерба от антропогенного воздействия.

**Выводы.** Анализ патентных баз данных с кластерной визуализацией на основе библиометрического подхода позволил кластерному анализу выделить наиболее перспективные направления исследований в области разработки биоэнергетических решений. Дальнейшие исследования будут направлены на разработку лабораторного стенда производства биогенного газа с возможностью комплексной переработки вторичного сырья и получением экологически безопасных дигестатов.

**КЛЮЧЕВЫЕ СЛОВА:** библиометрический подход, кластерная визуализация, биоэнергетика, технологические решения, моделирование, защита окружающей среды

## **Introduction**

The greenhouse effect of increasing carbon dioxide content in the atmosphere is the result of the long-term use of traditional non-renewable energy resources. These resources are being depleted rapidly. At the same time, the price of traditional non-renewable resources is gradually rising due to the increasing complexity of their extraction conditions, and the use of non-renewable resources is becoming economically less profitable [1].

The discovery of gas hydrates or methane hydrates in the submarine cryolite zone of the seas (Caspian, Black, Mediterranean, Okhotsk, Japanese, etc.) and the possibility of their exploitation could offset the problem of energy shortages on the planet for a while, but would further exacerbate the greenhouse effect [2-4].

Global production focuses on the development of energy-efficient and environmentally friendly technologies in all areas of human activity to solve existing problems related to the

depletion of traditional non-renewable energy natural resources, environmental pollution, and population growth. Primarily such technologies involve renewable energy sources, including biomass energy generated by livestock and agricultural waste, wood waste, plant biomass, marine phytoplankton plantations, and photobioreactor products [1, 5].

Considering the Kyoto Protocol requirements, several countries (Brazil, UK, Denmark, Germany, Ireland, Sweden, Finland, USA, etc.) offer the benefits to bio-energy plantation research with the purpose of direct utilization of atmospheric carbon dioxide and further use of biomass for energy generation. According to literary sources, biomass technical potential for energy purposes in the world could reach 500 MJ/year by 2050. This potential is roughly equivalent to the existing world biomass heat capacity produced in agriculture and forestry [6-8].

Potentially, the area occupied by highly productive energy crops plantations could be increased to 27 million hectares in Ukraine and 77 million hectares in the USA. The world's largest biofuel (ethanol) producer is Brazil. This country currently grows more than 7 million hectares of sugar cane as an energy crop. It can provide an additional 58-148 million hectares of land for energy plantations without affecting existing forests. In Indonesia, 27 million hectares of oil palm can be allocated to energy plantations [9-12].

The challenge in producing biofuels is to effectively reduce carbon dioxide from the atmosphere and generate energy from biomass. The ratio between biofuel energy and the energy used to produce biofuel should have a positive energy balance. However, the production of biofuels with zero or negative energy balances also takes place if a positive environmental effect is achieved as a result of producing clean energy at the consumption locations [13].

Nowadays, many countries (USA, Canada, Germany, Brazil, India, etc.) with considerable reserves of traditional energy resources

have already made significant technical progress in biofuel production and continue developing the bioenergy sector.

The advantages of bioenergy are obvious:

- reducing greenhouse gas emissions;
- sustainable development through using clean and renewable energy sources;
- reducing dependence on non-renewable energy sources;
- applicability versatility;
- agricultural economic growth, rural development;
- reducing production costs, improving the quality and competitiveness of goods;
- improving national security for countries with limited natural resources.

The process of anaerobic digestion of organic biomass (Fig. 1) with the production of biogenic gas (hydrogen and biomethane) and organic fertilizers (biocomposite or digestate) is becoming increasingly important for obtaining alternative energy sources [6, 14, 15].

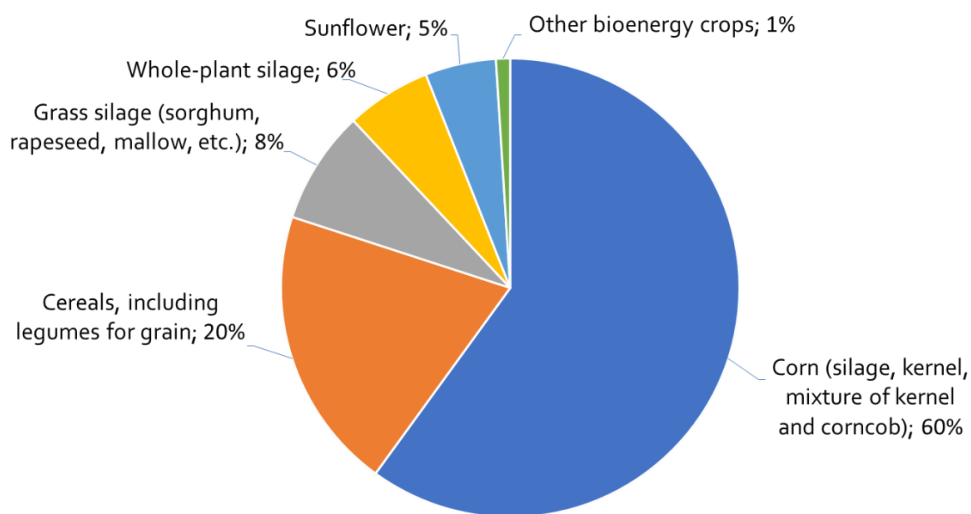


Fig. 1 – Share of different types of plant raw materials in biogas production in Ukraine [16]

The production and composition of biogas vary depending on the characteristics of the feedstock as well as the technological process. The main raw materials are energy crops that are grown specifically for this purpose (corn, cereals, sugar beet, and many others) and agricultural and livestock waste. These include organic wastes from food processing (e.g. press cake, grease trap waste), vegetable waste from wholesale markets, food waste, cut grass, material from landscape conservation activities, and organic waste from household landfills. The utilization of biogenic waste for biogas production

solves the problem of their accumulation in areas and the contamination of air and soil environment with substances generated by the decomposition of organics under inadequate disposal.

Different substrates have different productivity of biogas output; also, different rates of methane content in biogas. Currently, more than 60 different types of biogas technologies are in use or under development all over the world.

Calculations show that the use of all the energy plant biomass for producing biogas, compared to the production of biodiesel (uses only seeds) and bioethanol (uses carbohydrates) is

highly energy efficient. Furthermore, liquid or solid residues from the digestion process can be used as organic fertilizer due to their high nutrient content.

The production of energy from biogas is not related to the time of day, season, or weather conditions, therefore it can be produced continuously depending on the demand. In Germany, due to the fixed tariff for electricity supply from biogas, electricity, and heat are produced in the vicinity of the biogas plant, and this is the main way of using biogas. In the case of long distances between the place of production and use, biogas can be transported via gas pipelines.

Biomethane can be separated from other associated gases from biogas by wet purification under pressure, variable pressure adsorption, physical and chemical purification processes, and membrane technology [17].

The production of biomethane appeared in the focus of researchers and developers in many countries. The reason for this is significantly increasing the energy efficiency of this type of gas production process through the use of whole plant biomass for the production of biomethane and the opportunity to supply it to a common gas network with different uses.

Incomplete combustion of biomass in gas-producing furnaces produces generator gas: a mixture of flammable carbon monoxide (26-30%) with hydrogen (13-15%) and non-flammable nitrogen (45-55%) and carbon dioxide (5-8%). The heating value of generator gas varies between 10-13.4 MJ/m<sup>3</sup>. Generating gas can be used to produce heat, electricity, and liquid fuels as it does not require sophisticated equipment.

Gasification of coal with steam conversion and partial methane oxidation produces a

synthesis gas - a mixture of carbon monoxide and hydrogen - with a ratio of CO: H<sub>2</sub> gases from 1:1 to 1:3, depending on the method of production.

Biogas production is an efficient and investment-attractive technology due to the significant raw material resource potential, favorable natural and climatic conditions, and low-cost price of this type of energy. However, Ukraine is in the initial stage of implementing renewable energy sources. The technical and economic problems of biogas production and use are insufficiently studied [16].

Biogas plants can be set up as waste treatment facilities on farms, alcohol factories, sugar refineries, and meat processing plants. The biogas plant can replace a veterinary sanitary plant, which means that carrion can be utilized in biogas instead of producing meat and bone meal [18].

Among industrialized countries, Denmark has the leading position in the production and use of biogas according to relative indicators (biogas represents up to 18% of total energy balance). Based on absolute indicators for the number of medium and large plants, Germany leads with 8,000 plants. In Western Europe, at least half of all poultry farms are heated with biogas [19].

**Analysis of previous studies.** Based on several studies of scientific journals, indexed in the Scopus database, it appears that the bioenergy research topic was first discussed in 1998. There was a sharp decline in studies until 2007, thereafter the topic became increasingly popular. So far, the maximum number of studies was achieved in 2018, with 60 studies (Fig. 2). In 2019 and 2020, the research on this topic was decreasing due to quarantine measures and social movements.

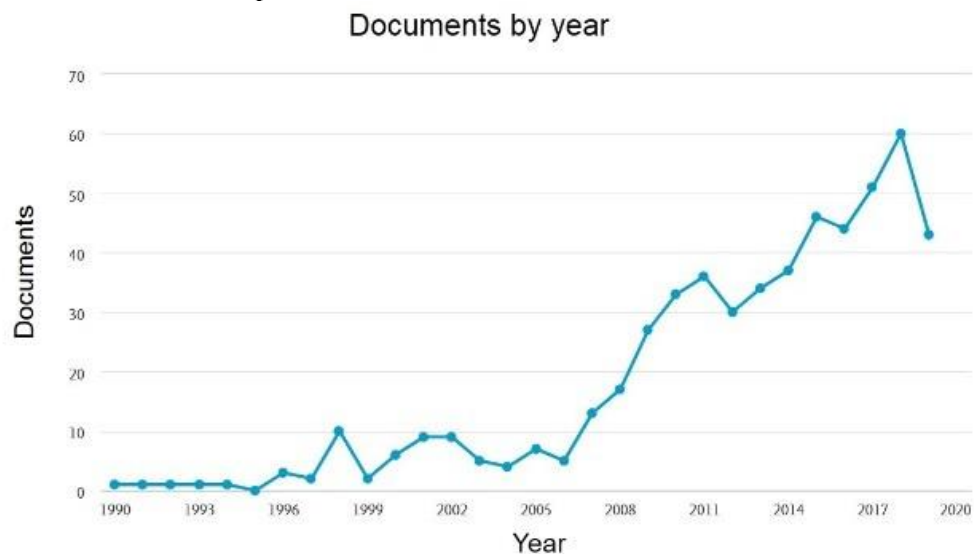


Fig. 2 – Analysis of search results by year

The bioenergy research topic is relevant in agrarian countries and countries with high amounts of organic waste. The United States of America takes the lead in the research on this topic and the number of publications - more than 100 scientific papers; then there comes China - 60 papers, Germany and England - more than 50 papers and Sweden - more than 20 papers (Fig. 3). The largest number of scientific studies is focused on improving the environmental situation in the

regions and the energy sector, biofuel production, and chemical engineering with the production of various useful chemical additives (Fig. 4). The main areas of research are also relevant to Ukraine.

Recently, Ukraine has seen a gradual increase in the number of facilities and installed capacity for biomass heat and power generation. Unfortunately, the pace of bioenergy development in Ukraine is far slower than in Europe,

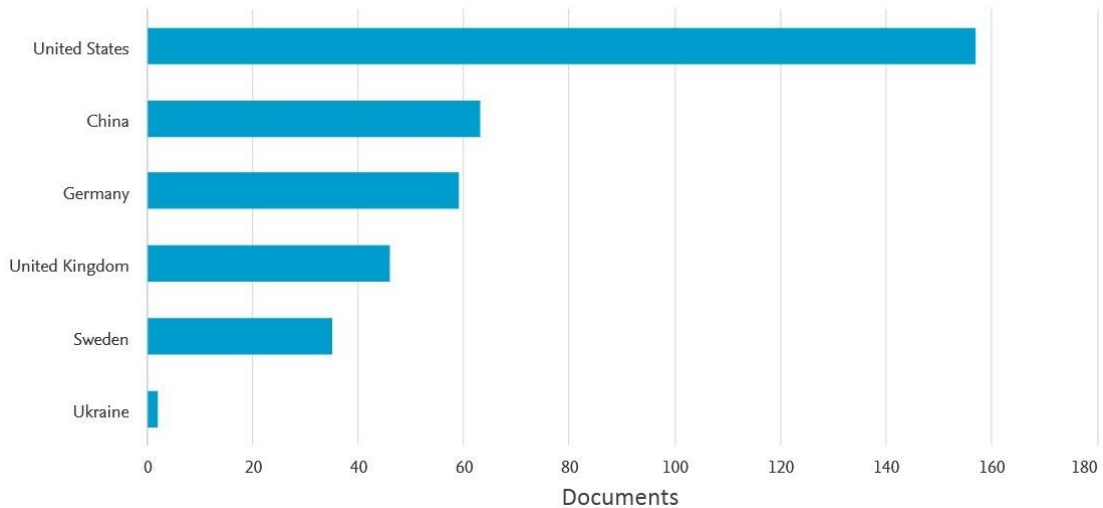


Fig. 3 – Analysis of search results by country

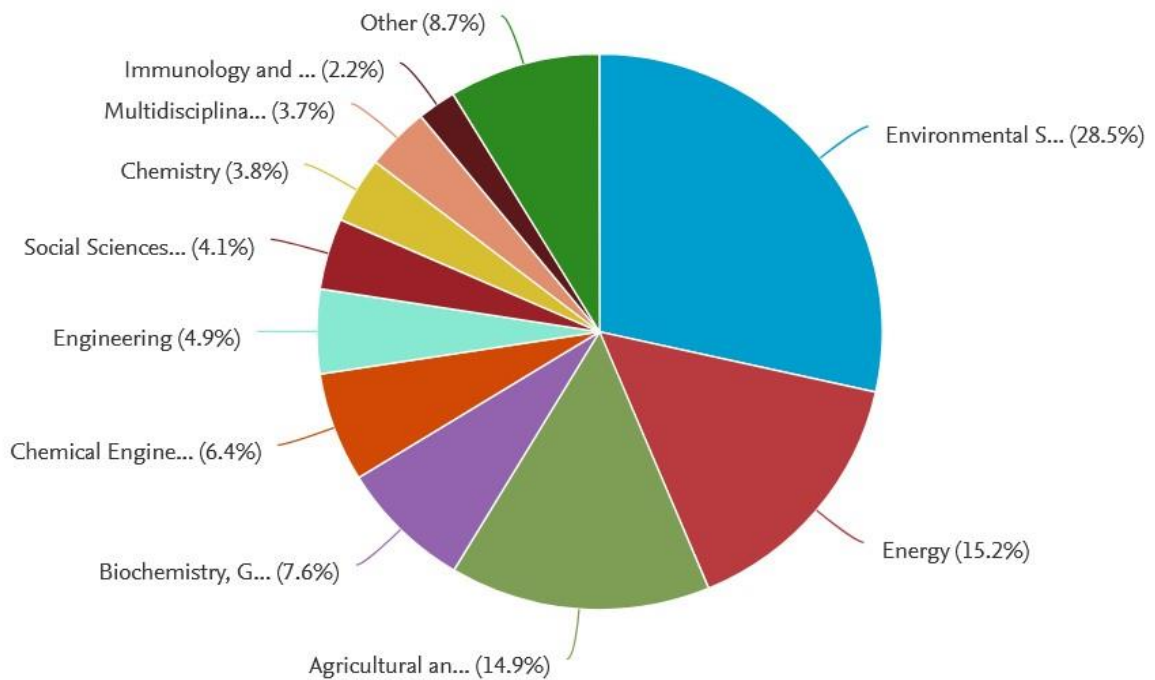


Fig. 4 – Analysis of search results by topic of research in the bioenergy technology field

but scientific research is continuing and developing. Intensification and efficiency improvement of biogas production is one of the main research areas in Ukraine. In research studies, the intensification of the anaerobic digestion process is achieved through the combination of feedstock [20, 21], pre-treatment [22, 23], and additives [24]. These developments are related to specific components of the production process. While in

foreign studies, intensification of biogas processes is discussed in the aspects of intensification of the anaerobic digestion process [25, 26] and complex intensification of the system incorporating biogas production [27, 28].

**The purpose of this study** is to model environmentally safe bioenergy trends based on national and international patent databases and scientific databases.

### *Objects and Methods*

The basic indicator of the effectiveness of innovation processes around the world is the publication and patent activity, which shows the scientific, technical and technological achievements in a particular area in different countries. Patent information was used from public sources: scientific journals and specialized websites [29]. The website databases contain patents registered in Ukraine (publications by Ukrpatent). The information has been studied according to the groups of the International Patent Classification for the

period from 2015-2020; patents are mainly classified in the following groups: B09B - disposal of solid waste; C05F - fertilizers from waste or refuse. The US, the Russian Federation, and the Eurasian Patent Database were also used. All selected patent documents were systematized by publication date for analysis.

VOSviewer software with bibliographic data from the *Scopus* database was used to visualize trends in the field of study.

### *Results and Discussion*

**Analysis of the implementation of technological solutions for biogas production.** In total, there are about 6.000 legal landfills in Ukraine and about 30.000 unauthorized dumps. There are about 1000 more landfills that are environmentally hazardous and do not satisfy the environmental requirements for landfills. Up to 300 dumps should already be closed and recultivated. The recycling rate in Ukraine does not exceed 7% of the total volume. Consequently, the issue of waste recycling in urban areas is very relevant; therefore, the development of renewable energy sources is essential to increasing environmental safety in the regions and green economy stimulation. Implementation of biogas plants that produce useful bio-based products, like biogas, can solve problems such as the disposal of organic and solid waste for different industries and the transition from stationary cogeneration plants to clean energy production [30].

Biogas plants have certain advantages over fossil fuels and other renewable energy sources [31, 32]:

- the combination of waste from seasonal factories (e.g. sugar refinery) and farm waste allows producing energy throughout the year;
- new workplaces or new income opportunities during the year for employees (e.g. for employees of the sugar refinery, in Ukraine they are

mainly located in small towns and are often the main employer of the city);

- modern agricultural waste management, most importantly with manure (lowering odor, remediation of soil, preservation of potential agricultural land that could be used as lagoons);
- step-by-step transition to a decentralized energy supply model for local communities.

According to the analyzed patents, an integrated diagram (Fig. 5) of the directions for patent solutions implementation was formed [32-52].

Each presented patent has its limitations and the following issues need to be covered to remedy them:

- reduction in the number of steel elements in equipment;
- creating equipment with an optimized design;
- development of efficient heaters;
- heating the biogas plant by solar energy;
- combining biogas production with other non-conventional energy sources;
- construction of large-scale production units for agriculture and cities;
- optimization of waste management;
- improvement of fermentation and initial degradation of waste by establishing active methanogenic bacterial strains using genetic engineering methods.

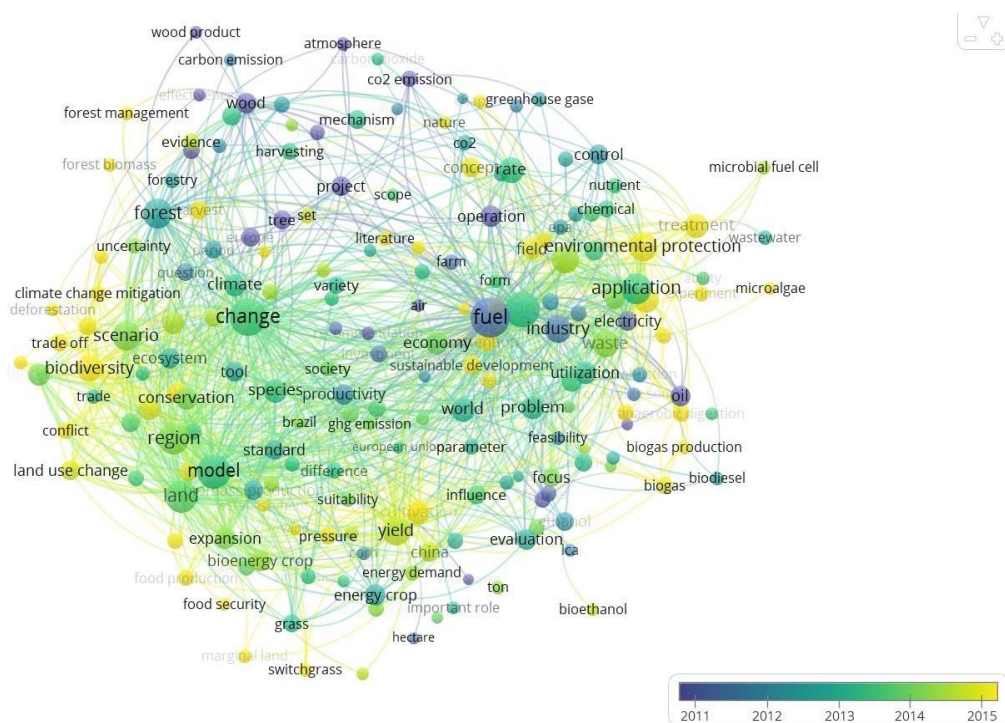




Fig. 5 – An overview diagram of the analysis of patent databases on the topic “Methods of producing biogas”







**Fig. 7** – Overall visualization showing the unit of measurement as the time since publication (Scopus database data)

Bioenergy is well developed in EU countries. According to an analysis by Banja et al., 2019, there are movements towards a capacity market mechanism to support biogas in the electricity sector, which slows down the pace of biogas introduction in the EU mature biomass electricity markets. Several EU countries continue to keep the dynamics of their biogas electricity markets alive. Still, biogas faces stiff competition with solar and wind energy sources and inexpensive natural gas, so further modernization of the biogas and biomethane production process is needed. According to Achinas et al. (2017) investments in anaerobic digestion are expected to succeed due to the low cost of available feedstocks - lignocellulosic sources (manure, fruits, vegetable waste) and the wide range of biogas applications. Research initiatives based on the article focused on improving anaerobic digestion control and its efficiency, i.e. microbial activity is a crucial parameter for process stability and biogas yield, and it requires further research. The article by Ferdeş et al. (2020), overviewed the enzymatic and biological pretreatment of feedstock for biogas production. Biological pretreatment is a highly effective method

for enhancing biogas production and the least expensive treatment applied to lignocellulosic biomass in the biogas production process. Future increasing the efficiency of enzyme preparations, as well as the capacity of microorganisms to transform the substrate, could be achieved by selecting new highly productive microbial strains and using molecular genetic techniques.

The impact of bioenergy technology solutions is critically discussed in Paolini et al., 2018. This paper shows that biogas can significantly contribute to the abate greenhouse gas emissions, but also provides the conditions for undesirable methane and N<sub>2</sub>O emissions (they are scarcely related to direct release from biogas combustion, whilst biomass storage and digestate management are the critical steps handling). In the medium-short term, digesters are considered preferable compared to untreated biomass according to the article. The upgrading to biomethane can generally improve air quality and reduce greenhouse gas emissions. However, methane losses in the off-gas may affect the sustainability of the whole process [53-58].

### Conclusions

Based on an analysis of current research trends, it is clear that the scientific focus is on improving biofuel production and the environmental

situation in the regions and energy sector. After comparing international studies with local research in the same field of methane fermentation intensify-

cation, we can see that international studies are more complex and cover the overall system.

The analysis of patent databases of technological solutions for biogas production highlighted the following directions of development: facilities for biogas production, bioreactors for different fermentation phases, machines for biological desulfurization of biogas, methods, and systems for solid waste processing. Based on cluster analysis,

the most common research topics are changes in bioenergy and its development models, reforestation, biofuel production and application, and the environmental impact of bioenergy technological solutions.

Further research will be focused on the development of a lab bench for biogenic gas production with the possibility of complex processing of secondary raw materials and obtaining environmentally safe digestates.

### Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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