Research on the recycling of organic waste by anaerobic co-digestion

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Abstract: *This paper aims to systematize knowledge on anaerobic co-digestion of biomass, having as main substrate organic waste, manure or sludge from treatment plants. The paper contributes to the transfer of knowledge on the recycling of organic waste in biogas plants in a sustainable and circular bioeconomy. It also presents a working procedure that identifies, both theoretically and experimentally, the optimal mixing ratio of biomass in biogas installations for anaerobic co-digestion. The authors' contribution is related to the interpretation of the different experimental tests performed in the laboratory and to the conclusions reached to identify the optimal mixing ratio of biomass for co-digestion in the pilot biogas plant where the experiments were performed.*

Keywords*: co-digestion, bioeconomy, organic waste, biogas*

JEL Classification*: Q2, Q57.*

Introduction

The paper aims to contribute to the transfer of knowledge on the recycling of organic waste in biogas plants in a circular economy and to present results of research conducted by the authors on identifying the optimal biomass mixing ratio for co-digestion of organic waste in biogas plants.

The transition of the economy to the circular economy and bioeconomy means the transformation of some industries but also the development of new technologies with beneficial consequences on the environment, in other words, "renewal of industries, modernization of primary production systems" [1].

The European Union is already a world leader in the sustainable use of natural resources in an efficient bioeconomy achieving sustainable development goals. The concern related to the conservation of resources and their sustainable use has created the premises for researching the possibility of capitalizing and recycling waste in order to use them as raw materials. Thus, the bioeconomy also means the development of new technologies that "pay attention to the aspects of ecological design, waste management and recycling" [2].

A category of waste that has great potential for recovery and recycling in a sustainable and circular bioeconomy is biowaste.

In accordance with the provisions of Directive 2008/98 / EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, biowaste is "biodegradable waste from gardens and parks, food and kitchen waste from households, offices, restaurants, wholesale warehouses, canteens, catering companies or retail stores and comparable wastes from food processing plants" [3]

Separate collection of biowaste, recovery and recycling as well as reduction of the amount of biowaste disposed of by landfill are recommendations established by Directive (EU) 2018/850 of the European Parliament and of the Council amending Directive 1999/31 / EC on landfills.

This regulation recommends that Member States "take measures to divert municipal waste from landfill so that by 2035, total municipal waste disposed of in landfills is reduced to 10% or less of total municipal waste generated (by weight)" [4].

At the same time, by 31 December 2023, EU Member States must apply separate bio-waste collection, encourage the recycling of bio-waste, encourage the production of compost in households and promote the use of bio-waste materials [4].

In Romania, Law 181/2020 on the management of compostable non-hazardous waste regulates "the development of compostable non-hazardous waste management activities, by recycling/recovery using the option of composting/anaerobic digestion, in order to protect human health and the environment" [25]. At the same time, the law requires local authorities to implement a system for the separate collection of biodegradable waste and to expand separate door-to-door collection of biowaste in urban areas, doubled by the implementation of the "pay as you throw" scheme and encourage individual composting in rural households". [25]

The law is not applicable since unfortunately the infrastructure for separate collection of biowaste and their transport has not been created, nor have the composting facilities and the anaerobic digestion facilities for biowaste been built, although these were provided in the National Waste Management Plan. [5]

Legislation on the circular economy

Concerns about "developing a sustainable, low-carbon, resource-efficient and competitive economy" [18] have materialized at EU level with the adoption of a 2015 Plan. European Union action plan for the circular economy.

New approaches to waste production, consumption and management are needed to move from a linear to a circular economy. The objectives set out in this plan are to keep products and resources as economical as possible and to reduce waste generation to a minimum.

Today, waste, including recyclables, is largely landfilled or incinerated, in a circular economy, it becomes valuable materials that are reintroduced into technological processes, with beneficial effects on the environment.

Through the adopted legislation, the European Commission recommends that Member States recycle waste and that its energy recovery is achieved only if the waste cannot be recycled or reused.

The European Commission has established a hierarchy for waste management, i.e. “an order of priority, from prevention, preparation for reuse, recycling and energy recovery to disposal in landfills” [18]. The recycling and recovery processes of energy recovery waste are also stipulated, as shown in Figure 1.

Thus, the incineration and co-incineration of waste with a high level of energy recovery, the transformation of waste into materials used as solid, liquid and gaseous fuels, are considered waste recovery technologies, while the incineration and co-incineration of waste with limited energy recovery are considered waste disposal technologies. At the same time, it can be seen that the anaerobic digestion of organic waste in which the digestate is recycled as fertilizer, is actually considered a recycling.

The percentage of waste recycling varies from country to country, there are countries where the recycling rate is 80% and others where the recycling rate is 5%.

At European Union level, only about 40% of waste produced by EU households is currently recycled, with significant differences between Member States and regions.

Figure 1. Waste hierarchy [18]

Although the circular economy aims to recycle waste and reintegrate it into the economy as a secondary material, there are concerns from industry about the quality of this material. Thus, at the level of the European Union, the elaboration of standards on the quality of secondary raw materials resulting from recycling is taken into account. A distinct and important category of secondary raw materials for which quality standards need to be developed are nutrients that could be reintroduced into the soil as fertilizers and thus their sustainable use in agriculture would reduce the need for mineral fertilizers [19].

Also, regarding the way plastic and plastic products should be designed, produced, used and recycled, at European Union level, Directive 904/2019 of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment in the European Union was approved in 2019 [20] and the brochure "A European Strategy for Plastics in a Circular Economy" was published [21]. According to these regulations, by 2030, all plastic packaging should become recyclable.

At the same time, in order to accelerate the transition to a circular economy, the European Commission is committed to adopting a new Action Plan for the circular economy.

Bioeconomy.

The transition of the economy to the bioeconomy means the transformation of some industries but also the development of new technologies with beneficial consequences on the environment, in other words, "renewal of industries, modernization of primary production systems". [22].

The European Union is already a world leader in the sustainable use of natural resources in an efficient bioeconomy to achieve sustainable development goals. At national level, the transition to a bioeconomy is slow, although in the National Strategy for Competitiveness 2015-2020, it is among the economic sectors with competitive potential. For these economic sectors identified with competitive potential, it is necessary to correlate “with the areas of smart specialization identified in the National Strategy for Research, Development and Innovation 2014-2020” [23].

Research and application of new technologies in areas such as food industry, biofuels, chemical industry, pulp and paper, green energy, can lead to remarkable results, this bioeconomy becomes a strategic direction for the development of a more sustainable industry and agriculture in our country.

By moving to an efficient and sustainable bioeconomy, environmental benefits will not be long in coming, such as "sustainable management of natural resources, mitigation and adaptation to climate change, reduction of dependence on non-renewable resources" [22].

Recovery of organic waste in Romania

In Romania, 4.95 million tons / year of municipal waste are generated annually, in accordance with the National Waste Management Plan [5]. The amount of biodegradable municipal waste generated in Romania is 3.84 million [5]. Currently, in Romania, biowaste is mostly disposed of in landfills. Due to their fermentation, large amounts of greenhouse gases are released, especially methane.

According to the National Inventory of Greenhouse Gas Emissions, it is found that, in 2014, the percentage of greenhouse gas emissions from the waste sector accounts for 5.15% of the total in Romania, increased compared to 1989 when they represented 1.71% of the total national GHG emissions of that year [6].

This increase is mainly due to the improper management of biodegradable municipal waste.

Currently, there is not yet an anaerobic digestion plant in operation for the recovery of biowaste in Romania, these being treated in mechanical and biological treatment plants and then disposed of in landfills.

In order to achieve the European targets for the recycling of organic waste, the National Waste Management Plan [5] provides for the mandatory construction of 32 facilities for anaerobic digestion with an estimated total capacity of 812,000 tonnes/year.

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In the National Waste Management Plan [5] the investment and operating costs for the analysis horizon 2018-2025 for the necessary investments in order to properly manage the waste were estimated at national level.

Consolidated financial flows, 2018 - 2025 are centralized in figure 2 [5]

Financial flows (million euros)							
Indicator	**Total**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
A.Investment							
A.1. Collection and transport							
Separate recyclable collection	182,476	-	178.833	3,643	-	-	- - -
Separate biodegradable collection	66,472	-	66,472	-	-	-	- - -
Residual collection	41,659	-	41,659	-	-	-	- - -
Total collection and transport	**290,606**	**-**	**286,963**	**3,643**	**-**	**-**	**- - -**
A.2. Fixed investment							
Transfer	-	-	-	-	-	-	-
Composting	3,940	1,182	2,758	-	-	-	-
Sorting - separately recycled waste	4,930	1,479	3,451	-	-	-	-
TMB with biostabilization	-	-	-	-	-	-	-
Anaerobic digestion	278,250	83,475	194,775	-	-	-	-
TMB with bio drying	226,636	-	-	24,484	135,982	66,171	-
incineration with energy recovery	136,324	-	-	13,632	81,794	40,897	-
other investment costs (design, supervision, project management, awareness information)	112,503	43,280	23,633	11,782	15,221	11,290	7,297
Total fixed investment	**762,583**	**129,415**	**224,617**	**49,898**	**232,997**	**118,358**	**7,297**

As it can be seen, the investments will be made for:

- the establishment of separate collection infrastructure for recyclable waste, biowaste and residue as well as for their transport, or together with mixed waste
- construction of composting installations, sorting facilities for separately collected recyclable waste, mechanical-biological treatment installations, anaerobic digestion installations inclusive for investments in waste incineration
- expansion of landfills and closure of non-compliant landfills [5].

If we analyse from an ecological and economic point of view the different methods of waste treatment, we will find out that the choice of a certain technology for recovery and disposal of waste will be made taking into account "local conditions such as population density, infrastructure and climate, such as and existing markets for associated products (energy and composts)." [24]

Considering that each tonne of biological waste subject to biological treatment by anaerobic digestion can produce between 100 and 200 m^3 of biogas [24] and, due to the potential for energy recovery from biogas and the potential for soil improvement residues (especially in the case of separate treatment of collected bio-waste), this solution can often be, from a financial and ecological point of view, the most advantageous treatment technique [24].

Anaerobic digestion of biowaste is a technology studied intensively and applied at Union level. Anaerobic digestion or co-digestion of biowaste in biogas plants can be performed in Romania only after researching and capitalizing on the results obtained in existing plants in Europe.

The optimal mixing ratio of biowaste for anaerobic co-digestion influences the amount of biogas produced with direct effects on investment return.

The research carried out worldwide for different substrates was studied and the working conditions, the type of reactors and the biogas production obtained were monitored as follows:

• digestion of municipal solid waste (52% organic fraction) mixed with residual sludge [7]. The experiments were performed in a semi-charge reactor operating in the temperature range 26-36 ° C, constant retention time (HRT) of 25 days and different loading rates (OLR) ranging between 0.5 up to 4.3 kg LV / m^3 · day. The maximum amount of biogas produced of 0.36 m^3 / kg LV was recorded for an OLR of 2.9 kg LV / m^3 · day.

• the influence of the concentration of total solids (TS) on the digestion process of organic waste (organic fraction of municipal solid waste, OFMSW) [8] for the concentration of solids (TS) of 20% and that of 30%. A batch-type reactor was used, in which, under mesophilic conditions (35°C), the waste was degraded for a period of up to 95 days. The experimental results showed that the reactor with 20% TS generated the highest amount of CH_4, i.e., 0.11 m^3 / kg VS compared to only 0.07 m^3 / kg VS in the case of the reactor filled with 30% TS.

- dry anaerobic digestion of municipal solid waste (MSW) [9] in mesophilic regime and a retention time (HRT) of 15 days, in a laboratory installation compared to the data from a pilot plant (with a capacity of 21 m^3). Total solids (TS) accounted for ~ 35% of the mixture. The results showed that following the fermentation process of the waste in the laboratory plant, between 0.187-0.211 m^3 CH_4 / kg LV were obtained depending on the concentration of total and volatile solids, as well as the ratio between introduced waste and the already fermented substrate. These values were almost identical to those obtained in the pilot plant, of 0.193-0.212 m^3 CH_4 / kg VS.
- (co) digestion of solid waste (organic fraction, OFMSW) and manure (from dairy cows, CM) in a pilot plant with two-stage anaerobic digestion [10]. The composition of OFMSW waste, representing ~ 61% of the total solid waste, was composed of approximately 62% paper (70% in co-digestion experiments), 23% (20%) food waste and 15% (10%) garbage. of the yard. Separate digestion (or mono digestion) of OFMSW and manure generated 0.03 and 0.08 m3 CH_4 / kg LV, respectively, while co-digestion produced 0.1 m^3 CH_4 / kg LV. The concentration of CH_4 in the gas produced during the tests varied between 72.3 and 73.1% (compared to ~ 60% obtained in conventional one-stage anaerobic digestion systems). The results showed that, in the co-digestion tests, the total mass of the matter subjected to fermentation was reduced by 78% after the digestion process (compared to only 8.7% in the tests with the use of OFMSW only). The conclusion is that the co-digestion of organic waste with animal manure has a positive effect on the biogas production process [10].
- the use of food waste (FW) in the process of anaerobic decomposition in batch type reactors operating under thermophilic conditions (~50°C) [11]. Prior to the tests, fresh FW waste added to the reactors was mixed with inoculum (sludge) obtained from an anaerobic fermenter at a municipal wastewater treatment plant. During the experiments the maximum amount of CH4 produced was 0.425-0.445 m^3 / kg LV after 28 days of fermentation (most part, almost 80%, was produced during the first 10 days). The average concentration of CH_4 recorded was of ~ 73% and that of CO_2 was ~ 27%. In terms of the substance introduced, the total amount of biogas generated was 0.465 m^3 of biogas per kg dry matter. These results show that food waste is a very good raw material for the production of biogas with a high yield.

- digestion of food waste (FW) in six batch-type reactors, in thermophilic regime (55° C), with three different concentrations of total solids (TS) in the mixture, of 20%, 25% and 30%, and two concentrations of inoculum (fermented sludge), 20% and 30%, the pH of the starting material was 5.9 for FW and 7.9 for fermented sludge and the C/N ratio was 37.0 in FW and 15.7 in fermented sludge [12] The best results were obtained for the batch with 20% TS and 30% inoculum. Methane production in the stabilization stage (between 20 and 60 days) was 0.49 m^3 / kg VS. They also proposed a protocol for improving the start-up phase in dry thermophilic anaerobic digestion systems for FW waste.

- the performances of the fermentation process of the wastes coming from fruits and vegetable products (FVW, 8.3% TS of which 93% VS) in mesophilic temperature regime (~ 35°C) and with the thermophilic regime (~55°C) [13]. The authors showed that better results are obtained in a thermophilic regime. Biogas production increases by almost 45%, i.e., for a loading rate (OLR) of 1.24 kg LV / (m^3 · day) 0.48 m^3 biogas / kg LV was obtained under thermophilic conditions and 0, 33 m^3 biogas / kg LV under mesophilic conditions. The concentration of CH4 in the generated biogas was the same in the two experiments (58%). The authors observed that biogas production increases considerably if FVW waste is co-fermented with slaughterhouse (AW) waste. In the mesophilic regime the amount of biogas produced was 0.58 m^3 / kg LV while in the thermophilic regime it was 0.73 m^3 / kg LV. This is attributed to a better C/N ratio of the FVW + AW mixture in the co-fermentation process (~ 22 compared to ~ 34 in FVW) [6].

- co-digestion of OFMSW with vegetable oil, animal fats, cellulose and protein was also investigated [14]. The best performances were obtained for the mixture between OFMSW and vegetable oil, with a biogas production of 0.699 m^3 CH_4 / kg VS which represented an increase of> 80% compared to OFMSW mono-digestion.

- co-digestion of OFMSW with fruit and vegetable waste [15] showed that for the batch with a mixture of OFMSW and FVW of 1 to 3 (VS mass ratio) the best performances were obtained. Cumulative biogas production increased to 0.494 m^3 / kg LV, an increase of almost 130% compared to the case of OFMSW mono-digestion, and the methane concentration increased to 79.7% (compared to 76.5% in mono-digestion).

Taking into account the results of international research, biogas plants have been built in Europe in which organic waste, including biowaste, is recovered.

Table 1. Examples of large biogas plants from co-digestion of organic waste [16]

Name of biogas plant (country)	substrate	digestor capacity	working conditions	biogas production
Vasteras (Sweden)	kitchen waste separated at source (14000t/ year) + energy biomass(5000t/year) + fats from kitchen and restaurants(4000t/year)	4000m^3	Mesophilic (37 °C) Hydraulic retention time=20 days	6290m^3/day biogas upgraded
Linkoping (Sweden)	slaughterhouse waste (55%) + food waste (45%)	two reactors 3800m^3 each	Mesophilic (38 °C) Hydraulic retention time=30 days	63 GWh/year biogas upgrated
Ludlow (England)	kitchen and garden waste(5000t/year)	900m^3	Mesophilic (40 °C) Hydraulic retention time=25 days), Total solids=12%, pH=7,3-7,5	100-140m^3/t waste
Otelfingen (Switzerland)	biological waste separated at source(10000t/year) + supermarket food waste (2500)	900m^3	Thermophilic(55°C) Hydraulic retention time=14 days), Total solids=30%,	100-130m^3/t waste

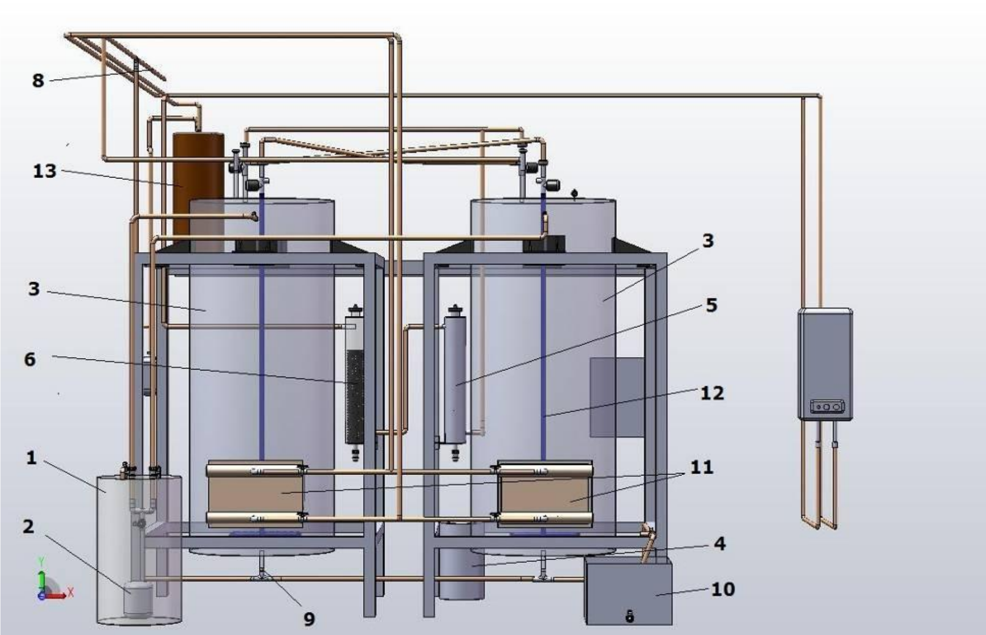
Therefore, food waste is a very good raw material for the production of biogas with a high yield. It was also found that the process of anaerobic digestion of organic waste by co-fermentation with other types of waste leads to increased efficiency of the biogas plant.

Experimental research on anaerobic digestion of organic waste in Romania
At the Romanian level, there is research on mixing recipes for co-digestion and examples of good practices for biogas plants that use biomass from agriculture, animal manure and sludge.

Research has shown that the optimal mixing ratio of biomass for anaerobic co-digestion influences the amount of biogas produced with direct effects on return on investment.

The determinations were performed using a patented pilot plant for the production of biomass biogas - Patent no. 122047, "Process and installation for the production of biomass biogas [17]

Figure 2. Schematic diagram of the pilot plant [17]



From the tank where the biomass is deposited, the biomass passes through a mill, and then it is sent to the tank where it is homogenized with water (1). The homogenized material is transported with the submersible pump (2) and sent to the fermenters (3). This installation is also provided with a tank containing a correction agent (4) which ensures the pH. The resulting biogas is passed through a filter (5) which retains H_2S (hydrogen sulphide) and then through a system (6) which partially retains CO_2 (carbon dioxide), after which it can be compressed in the adjacent system (7) and the biogas resulted is collected through pipes (8) for use. The used material is discharged through a gravimetric system (9), and part of the resulting liquid is separated (solid from liquid by settling) through the system (10) and sent to the sewer. The reactors are heated by the heating system (11), and the homogenization is performed by a bubbling system (12). In order to store small amounts of biogas for analysis, the plant is also equipped with a smaller supply tank (13). [16]

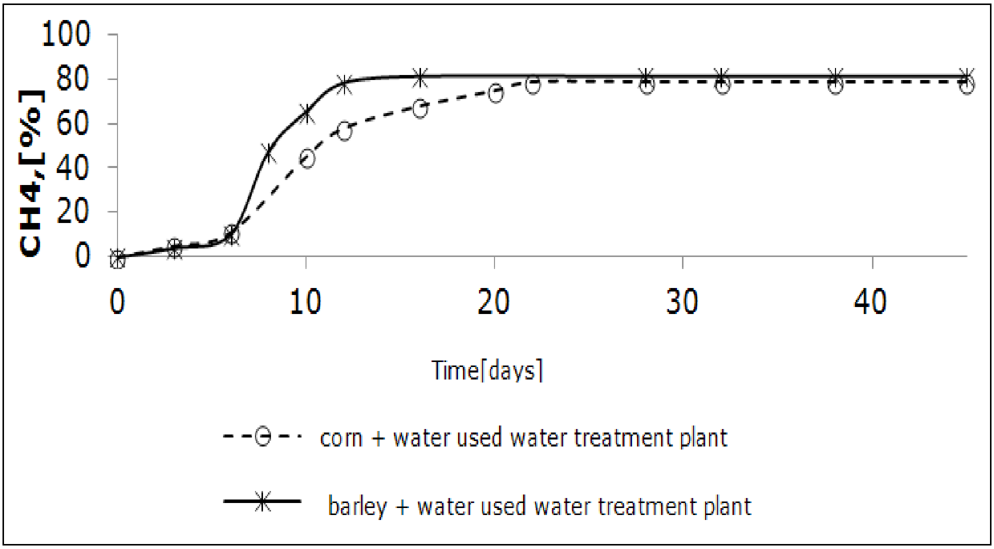
Obtained results:

Laboratory tests and analyses were performed for several combinations using materials of cereal origin, respectively industrial and urban wastewater.

For the degraded cereal materials, combinations with wastewater from a brewery and a treatment plant, both located in Timisoara, were used, the results identifying the potential to produce qualitative biogas on a pilot scale.

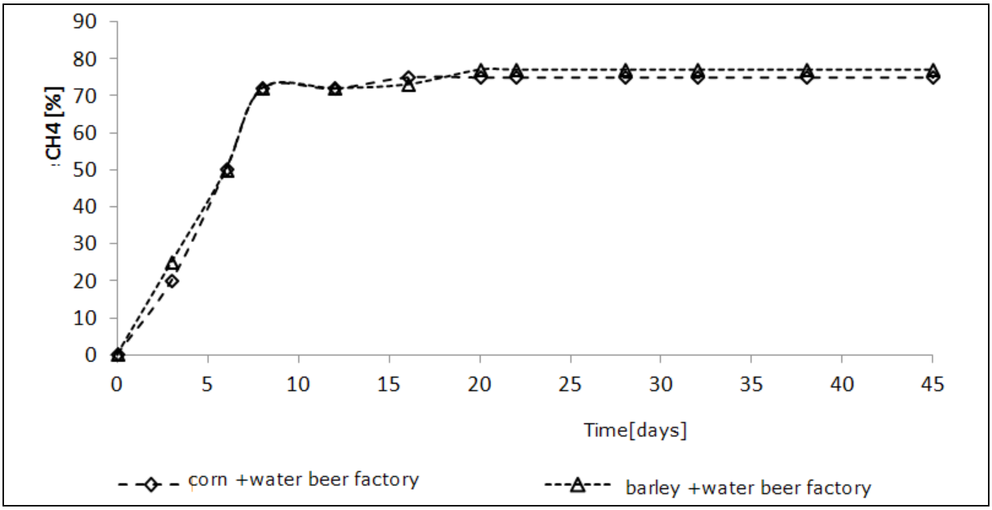
It has been found that different types of degraded grain materials are compatible with different liquid substrates from various sources. Thus, the batch containing degraded barley and wastewater from the treatment plant best covers both the qualitative and quantitative aspect of the biogas produced, compared to the other batches tested.

Figure 3. CH_4 concentration [%] [16]



The methane concentrations obtained for the batches containing cereal materials and wastewater from the brewery well cover both the qualitative and quantitative aspect of the biogas produced. Comparing the two graphs presented, it is observed that the batch containing degraded barley and wastewater from the treatment plant best covers both the qualitative and quantitative aspect of the biogas produced, compared to the other batches tested.

Figure 4 CH_4 concentration [%] [16]



Conclusions

The process of anaerobic digestion of organic waste, including biowaste, is a complex process influenced by a number of factors and process parameters.

Anaerobic co-digestion of organic waste by co-fermentation with other types of waste or wastewater leads to its improvement and to increase the efficiency of the installation.

An essential element is to establish the optimal recipe for anaerobic co-digestion of organic biowaste with other types of waste.

The infrastructure level needed to carry out research exists at the University in order to determine the optimal mixing recipe, but this is insufficient. It is necessary to involve the private environment in concluding partnerships with Universities in order to conduct research on the co-digestion of organic waste.

It is also necessary to intensify research to establish the optimal recipes for anaerobic co-digestion of organic biowaste with other types of waste, so that biogas plants that will be designed and built in Romania will operate at maximum biogas production yields. These researches can be carried out by the local public authorities, responsible for the construction of biogas installations [5], in partnership with the Universities that have laboratories equipped with pilot biogas installations. Such research can be performed using laboratory equipment consisting of an automatic methane potential testing system - AMPTS II, developed by Bioprocess Control Sweden AB (BPC), which has 15 digesters with a total volume of 600 ml within the Centre of Research of the Polytechnic University of Timişoara, Faculty of Mechanical Engineering which has such equipment

The research will be able to establish the optimal network and will quantify the economic and environmental benefits of anaerobic co-digestion of organic bio-waste with other types of waste in biogas plants, in a sustainable and circular economy.

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