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# Biogas production from textile waste

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***Abstract*—An examination of the procedure for fermenting textile waste to create biogas is provided in this study. Therefore, it is essential to study the various fermentation process reactions as well as the various factors affecting the anaerobic digester's performance in order to assess a methanization unit producing biogas. A paste and liquid sludge mixture was put into the digester. The study showed that, over the course of 21 days, textile sludge can produce biogas by mesophilic fermentation at a maximum pressure of 2 bar.**

***Keywords*— Fermentation – biogas – Digester – Textile waste – Pressure**

## I. INTRODUCTION

An inventive method of waste management and the creation of renewable energy is the biogas production from textile waste. Textile waste can include a wealth of organic materials that are appropriate for anaerobic digestion, a process that turns organic matter into biogas. This includes scraps, damaged fabrics, and end-of-life clothing.

The role of wastewater treatment plants is to eliminate the pollution contained in domestic effluents, before their release into the natural environment. If the water, at the end of treatment, is effectively purified, the initial pollution is partly stored and concentrated in the sludge resulting from the various stages of water treatment. This sludge is then considered as recoverable waste, which must be eliminated while respecting certain regulatory constraints.

The production of sludge is increasingly difficult to manage. This pushes governments to seek technological solutions to reduce it in the same way as the management of other types of waste.

One of the effective and less expensive technologies allowing the treatment of the organic fraction of this waste is anaerobic digestion (bio-methanization), which consists of a biological degradation, in the absence of oxygen, of the organic matter into a mixture of methane (CH4) and carbon dioxide (CO2) called `biogas'. Thanks to anaerobic digestion, waste becomes a source of wealth. This technology becomes essential in the process of reducing waste volumes and producing biogas, which is a renewable energy source that can be used in the production of electricity and heat.

Alternatives to manage the polluting potential include strategies to reduce textile waste and extend product life, such as renting and mending clothing, the second-hand market, and reprocessing processes for the creation of new or original items [1]. Fast fashion, on the other hand, has advanced along a business model that creates enormous quantities of apparel and trends at low prices [2], frequently with poor quality. Due to their poor quality, textiles can only be used for energy recovery, which is at the bottom of the waste management hierarchy, as specified by Directive 2008/98/EC [3].

Anaerobic digestion (AD) is a widely used biotechnology that has shown to be an efficient green waste management solution by lowering the risk of contamination and generating biogas, which is used as electricity. Using AD in the textile sector can help with water reuse and waste use as a resource for sustainable energy production. However, if AD is used as the only strategy, the variety of chemicals, organic pollutants, and recalcitrant compounds (such as polyacrylates, phosphonates, alkyl phenol ethoxylates, chloroform, heavy metals, and cotton-based recalcitrant material [4]) present difficulties and lower the degradation efficiency [5].

According to a number of studies, applying pretreatments can help enhance the degradability of organic matter while also increasing the yield of biogas [5,6,7,8] and removing harmful chemicals and colors from wastewater and solid waste in aqueous solutions [9, 5]. The chemical composition of the waste affects the effectiveness of pretreatments, which can be chemical, physical, biological, or mixtures of these [10].

Physical pretreatments, such as heat, mechanical force, irradiation, and ultrasound, cause cell disruption [11]. As a result, by decreasing the particle size, the organic matter's contact surface is enhanced, which makes microbial

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attack easier [12]. Physical pretreatments are advantageous because no hazardous compounds are produced, but some methods (such as heat) can raise energy expenditures to the point where they are not practical on a wide scale [12]. Chemical pretreatments, such as acid, alkali, and organic solvents, work by rupturing chemical bonds in intricate structures, which causes the cell to inflate internally and increase its surface area [13].

Chemical methods are more frequently used than biological and physical pretreatments because they are extremely effective in breaking down complicated materials [13]. However, they need to be handled carefully because harmful compounds may arise depending on the chemical reagents used. Certain chemical pretreatments, like nitric acid (HNO3), hydrochloric acid (HCl), and sulfuric acid (H2SO4), can cause metal to corrode and fail, further damaging operational equipment [14,15,16].14, 15, and 16. Enzymes, fungus, bacteria, microbial consortia, and other biological pretreatments work in concert with microbial metabolism to hasten the breakdown of organic materials [12]. Wu et al. [18] numerically examined a 3-dimensional model of biogas production. The model is based on the principles of conservation of mass, energy, species transport and chemical reactions. The simulation results showed that biogas production is sensitive to variation in the concentration of organic matter and fermentation time. Jurgensen et al. [19] proposed a dynamic approach for improving biogas production. The numerical model used is a statistical model for single reactor technology. The simulation results showed good agreement with the experimental studies. Lubken et al. [20] modeled the energy balance of anaerobic digestion for the case of livestock manure. The simulation method is hard ADM1 base. The simulation results made it possible to calculate the production of biogas and methane as well as the energy produced. Using a pilot-scale reactor, the authors demonstrated the usefulness of using the dynamic energy balance model. Gebremedhin et al. [21] presented a numerical model based on the principles of energy conservation. This model is used to calculate the daily, monthly and annular energy demand during the fermentation process. Hill [22] presented a numerical model for the analysis of the kinetics of methane fermentation. The model is based on two criteria: the maximum volumetric methane productivity or the maximum daily methane production. Indeed, the concentration of volatile solids, the fermentation time and temperature are the main factors in determining the maximum daily methane production. Sokolenko et al. [23] studied the evolution of energy during the fermentation process in the liquid and gas phase. The results showed that the concentration of carbon dioxide increases in the mass transfer phase and decreases upon reaching the saturation pressure of the liquid phase.

Opwis et al. [24] developed an innovative technology for the production of energy from textile wastewater. The results showed that the proposed semi-industrial system produces a large amount of biogas. Rajendran et al. [25] studied the economic and experimental evaluation of a new biogas digester. The influential materials used are municipal solid waste. The results showed that the proposed domestic digester has economic and environmental benefits. Control parameters such as temperature, pressure, sludge concentration, climatic parameters and mechanical agitation are the factors to be optimized. Indeed, Guo et al. [26] developed a digital thermal model to investigate optimal temperature and organic matter conditions. Galanakis et al. [27] studied the effect of pressure and temperature during the fermentation process. The results showed the sizing of the bioreactor is limited by the hydrostatic pressure.

Preventing the introduction and production of toxic chemicals encourages the development of an ecologically sound AD system. Additionally, even at full scale, the application of biological approaches is highly attractive due to the reduced energy and capital costs when compared to physical and chemical pretreatments [15, 17].

To boost the production of biogas, prior research has involved pretreating waste textiles that contain high crystalline cellulose and cellulosic blend fibers in a batch assay [28], [29]. Furthermore, two-stage testing procedures were never used on textile wastes.

During the anaerobic digestion process, only part of the organic matter is completely degraded, the rest is an excellent fertilizing agent for agricultural land. Waste textiles, which are primarily made of cotton and viscose fibers, have a large potential for producing various biofuels, including biogas, because of their cellulose content [30].

As part of this research project, the process of anaerobic digestion of activated sludge from the textile wastewater treatment plant for biogas production was considered. This is an applied research partnership between our research laboratory (LESTE) and the Société Industrielle de Textile SITEX. The recovery of textile waste contributes on the one hand to preserving the environment and on the other hand to producing ecological, green and sustainable energy.

This study presents an analysis of the process of fermenting textile waste to produce biogas. Thus, to assess a methanization unit producing biogas, one must research the various fermentation process reactions as well as the various factors influencing the anaerobic digester's performance [31, 32]. Through the concentrations of various reagents and products, the numerical model tracks the evolution of the reactions that occur, allowing us to examine the effects of various biological control parameters and system performance.

## II. EXPERIMENTAL DEVICE

In this study we are interested in a mesophilic methanisation in an anerobic digester. Thus, mesophilic methanization means that the digester is maintained at a temperature approximately equivalent to that of the human body: between 35 and 40°C. This is the most widespread operation, whether for agricultural or industrial installations. Among the advantages of mesophilic fermentation, we can cite:

* Optimal temperature: Mesophilic bacteria thrive at moderate temperatures, usually between 20°C and 45°C. This temperature range is easier to maintain in fermentation reactors, reducing energy costs associated with heating or cooling.

*Flexibility of the substrate: Mesophilic bacteria can tolerate a greater variety of organic substrates. This implies that they can produce biogas by fermenting a range of organic materials, including food waste, yard waste, and textile waste.

*Fermentation Speed: Bacteria that are thermophilic (which grow best at higher temperatures) typically grow at a slower rate than mesophilic bacteria. This typically translates to shorter retention periods in fermentation reactors, enabling the generation of biogas more quickly.

*Lower maintenance costs: Fermentation systems employing mesophilic bacteria can often require less maintenance and be easier to manage than those using thermophilic bacteria because of their lower operating temperature and tolerance to a wider variety of substrates.

Anaerobic digestion is a complex process. The principle is as follows: organic waste is stored in a cylindrical and airtight tank called a “digester” or “methanizer” in which it is subjected to the action of micro-organisms (bacteria) in the absence of oxygen, the digester used is shown in this figure: it is a cylindrical stainless steel digester with a radius R = 45 cm and a height of 60 cm. A digester made up of two coaxial cylindrical enclosures is proposed. The sludge will be placed in the inner cylinder. To ensure its homogenization, an agitator is installed. It is driven by an electric motor with a power of approximately 2.2 kW. À It eliminates any type of decantation at the bottom of the digester. The free space between the two coaxial cylinders serves as a bath filled with hot water, the temperature of which is controlled by a thermostatically controlled bath. A pressure sensor installed inside the digester installed on an acquisition card and a microcomputer allowing the monitoring of the gas pressure generated during the fermentation reaction. The temperature control is done by installing two thermocouples inside the digester and near its wall,

Fig. 1 Experimental device

Thus, a mixture of paste sludge (75 kg) and liquid was placed in the inner cylinder of the anaerobic digester (Figure 2).

Fig 2 textile sludge liquid (a) and paste (b)

To prevent textile sludge from decantation, an electric motor-powered agitator is put inside the digester. A pressure sensor (0 bar -16 bar) was installed inside the digester to control the pressure of the gas generated during the fermentation process. Two thermocouples were installed, one inside the digester and the other near the wall, to control the temperature. These sensors are installed on an acquisition card connected to a microcomputer, allowing the temporal evolution of pressure and temperature to be visualized.

## III. EXPERIMENTAL STEPS

Anaerobic fermentation can be used to produce biogas from textile waste, both in liquid and paste form. Despite not being thought of as a source of substrate for biogas production, textiles frequently contain organic materials that, in anaerobic environments, can be broken down by microorganisms to produce biogas. This is how it might function:

*Textile waste needs to be pretreated before it can be used in anaerobic fermentation. This applies to waste that is liquid (such as wastewater from dyeing or washing operations) or paste (such as rags and unusable clothing). In order to improve the specific surface area and make it easier for microorganisms to access the substrates, this may entail grinding, fragmentation, or other pretreatment techniques.

*Microorganism inoculation: The textile waste that has been pretreated is subsequently put into an anaerobic fermentation reactor. To start the fermentation process, cultures of mesophilic bacteria or other anaerobic microorganisms are added to the reactor.

*Anaerobic fermentation: The organic matter in textile waste is broken down by microorganisms in a fermentation reactor. Volatile fatty acids, alcohols, and other intermediate products can be produced from the polymers of cellulose, lignin, and other organic compounds found in textiles. Anaerobic microorganisms then break these compounds down into biogas, primarily methane (CH4) and carbon dioxide (CO2).

*Biogas production and utilization: The fermentation reactor's waste product, biogas, is collected and can be used to generate fuel, electricity, or heat. Additionally, it can be refined to create biomethane of a commercial grade that can be introduced into the natural gas grid.
Residue Management: After fermentation, the remaining fermented residue, often called digestate, can be used as a fertilizer or amendment for agricultural soils due to its high nutrient content.

## IV. MATHEMATICAL MODEL

The biological reactions involved in methanization are complex but overall we can identify three main stages: hydrolysis and acidogenesis: the complex organic chains (proteins, lipids, polysaccharides) are transformed into simpler compounds (fatty acids, peptides, amino acids); acetogenesis: the products of acidogenesis are converted into acetic acid; methanogenesis: acetic acid is transformed into methane and carbon dioxide,

We employed the COMSOL 5.6 software to examine the fermentation processes occurring in the digester. The following is a list of the two fundamental chemical reactions that constitute methanogenesis:

$C_2H_4O_2 \Rightarrow CO_2 + CH_4$ (eq. 1)

$CO_2 + 4H_2 \Rightarrow 2H_2O + CH_4$ (eq. 2)

Mass transfer equation: to evaluate the different concentrations of reagents and products during methanization we used the Arrhenius law:

$$K^f = A^f \left(\frac{T}{T_{ref}}\right)^{nf} \exp\left(-\frac{E^f}{R_g T}\right) \qquad \text{(eq. 3)}$$

Where:
Af: direct frequency factor
nf: direct temperature exponent
Ef: direct activation energy
Tref =1 K

## V. NUMERICAL RESULTS

COMSOL 5.6 was used to examine the fermentation process occurring in the digester.

This figure 3 illustrates variation in molar concentration of different constituents of textile sludge during the fermentation reaction. It should be emphasized that the amount of biogas generated mainly depends on the amount of organic matter present, in particular the amount of acetic acid.

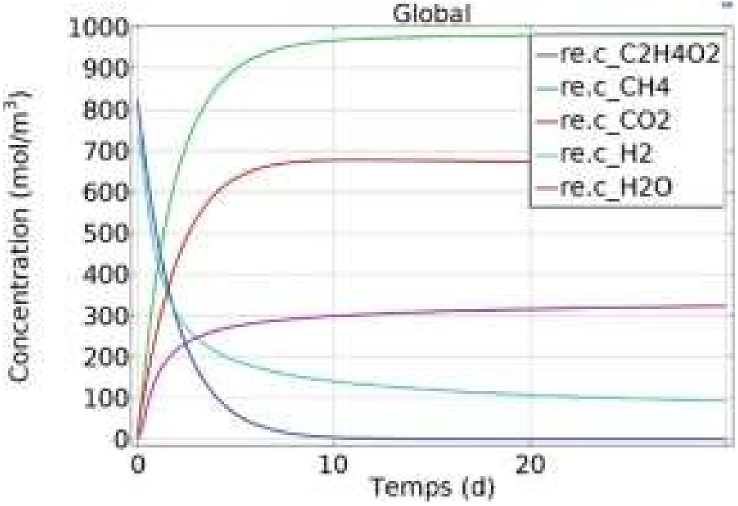

Fig 3 Molar concentration of reactants and products of textile sludge fermentation

The amount of biogas generated mainly depends on the amount of organic matter present, particularly the amount of acid.

The results of the heat balance for mesophilic (35 °C) conditions are shown in Figure 4. This figure shows that 88% of the total heat required was used to compensate for heat losses through the digester's walls (Qd) and raise the sludge's temperature to that of the digester (Qi). In actuality, heat transfer through the digester walls loses 63% of the total heat required for digestion (Qd ). Therefore, to guarantee the digester's best performance, thermal insulation needs to be applied to its walls. It should be mentioned that the amount of heat needed depends on the outside temperature of the digester as well.

In fact, when the temperature difference between the digester's interior and exterior decreases, Qd and Qi values also decrease, thereby lowering the overall heat requirement. Thus, another 33 kJ is obtained.

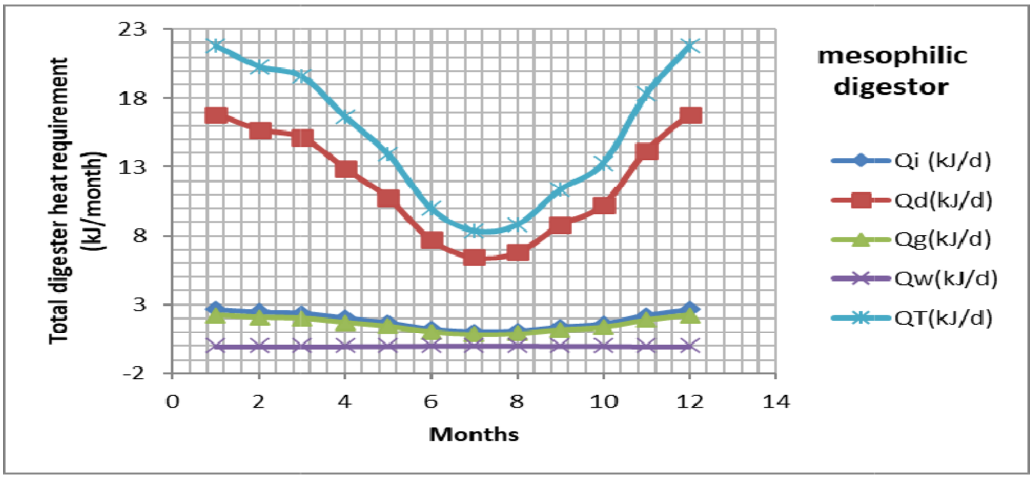

Fig 4 Evolution of the monthly heat balance during the mesophilic fermentation process

With:
Qi: heat loss inside the digester
Qd: heat loss near the wall
HQ: heat loss during gas extraction
Qw: heat loss during evaporation
QT: total heat loss

Thermal insulation must therefore be applied to the walls of the digester to guarantee optimal operation.

## VI. EXPERIMENTAL RESULTS

- Temperature control

Many processes in a variety of industries, such as the production of biogas, chemicals, food, and pharmaceuticals, depend heavily on temperature control. Strict adherence to temperature requirements guarantees process effectiveness, safety, and high-quality products.

Temperature plays an essential role since methanogenic bacteria are particularly sensitive to temperature variations. The fermentation process should be carried out with a maximum variation of ± 1°C.

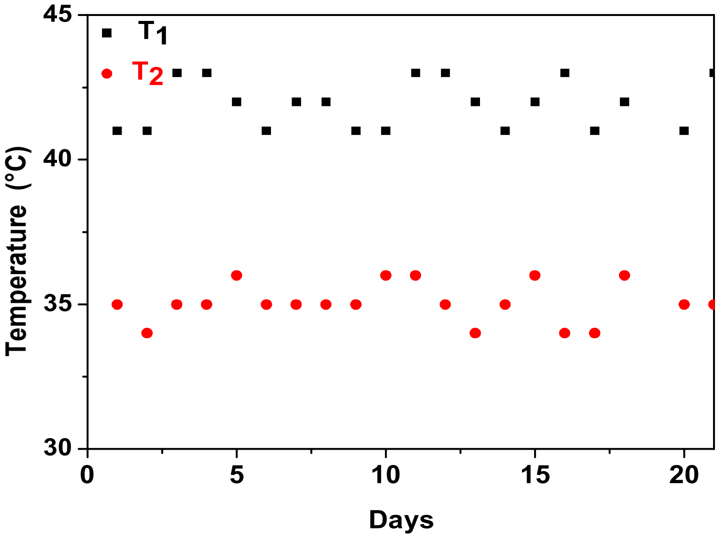

Fig 5 Temperature control

The internal temperature is practically uniform (35°C -36°C), it is a mesophilic fermentation characterized by a moderate temperature.

- Pressure sensor calibration

Let's now move on to the presentation of some experimental results. We must start with the calibration of the pressure sensor to ensure the accuracy and reliability of the measurements, calibration of pressure sensors is an essential step in ensuring accurate and dependable pressure sensor measurements: calibration generally consists of applying known pressures and comparing the output values display by the quad (voltage) to the corresponding input values. Adjustments are made until the output exactly matches the input. The adjustment curve is shown in Figure 6.

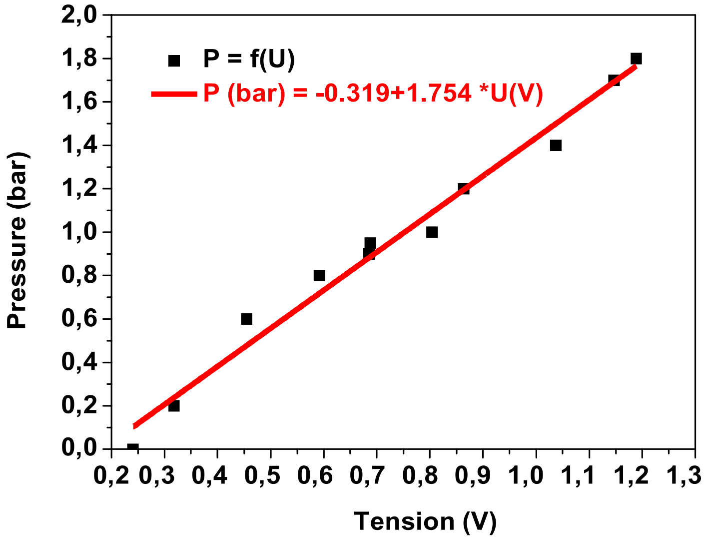

Fig 6 Pressure sensor calibration curve

- Daily production of gas pressure

The quantity of gas produced or the pressure level sustained within a particular system over a 24-hour period is referred to as the daily production of gas pressure. In many industries, such as manufacturing, utilities, and oil and gas, measuring daily gas production or pressure is essential because it affects production processes, safety, and efficiency.

The daily evolution of the pressure inside the digester is shown schematically in figure 7.

The variation in pressure tells us directly about the quantity of biogas produced and subsequently its concentration, We notice that the production of biogas begins from the 7th day with slow kinetics.

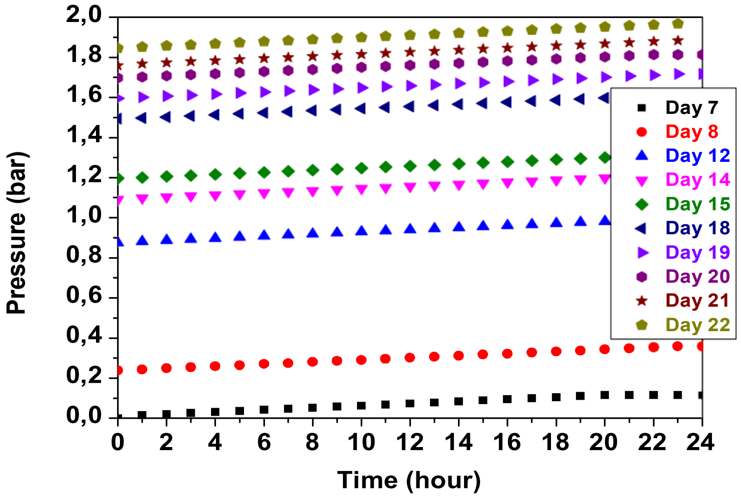

Fig 7 Gas pressure produced during fermentation for each day

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- Biogas production kinetics

The study of the rate at which biogas is produced during anaerobic digestion is known as "biogas production kinetics." This process is usually represented mathematically, with key factors influencing gas production over time being described in relation to one another. Anaerobic digestion process optimization, gas yield prediction, and the design of effective biogas production systems all depend on an understanding of the kinetics of biogas production. Biogas production kinetics are shown in Figure 8.

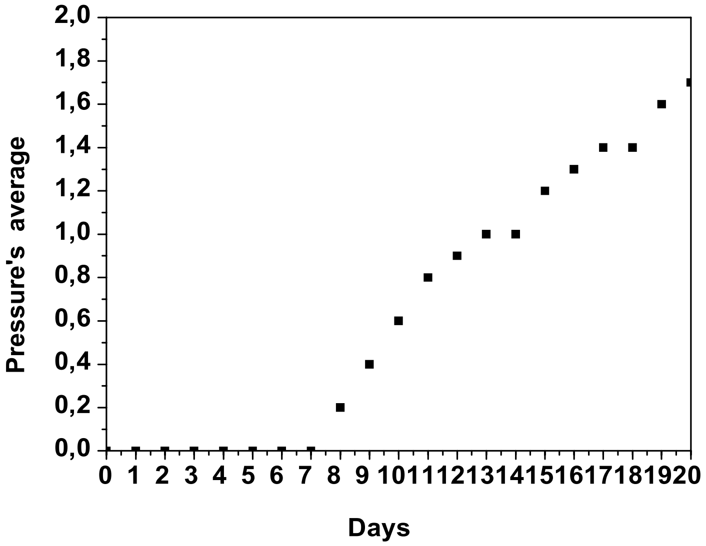

Fig 8. Biogas production kinetics

## VII. CONCLUSIONS

A study of the fermentation of textile sludge for biogas production in an anaerobic digester was carried out: a mixture of liquid sludge and paste was introduced into the digester. Although biogas production from textile waste can present specific challenges due to the nature of the materials, it also offers an opportunity for waste valorization and renewable energy production from unconventional sources.

This article looks at the numerical simulation of textile wastewater's anaerobic fermentation process. The outcomes demonstrated that spontaneous fermentation reactions can occur in a direct manner in ambient temperature.

The results showed that textile sludge is capable of producing biogas via mesophilic fermentation with a maximum pressure of 2 bar during a stay of 21 days.

The evolution of the biogas concentration during mesophilic fermentation shows that the quantity of biodegradable organic matter in the sludge affects the volume of biogas produced as well as the fermentation time required.

The evolution of the internal pressure of the digester is proportional to the quantity of biogas generated.

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## REFERENCES

[1] 1.Piribauer, B.; Bartl, A. Textile Recycling Processes, State of the Art and Current Developments: A Mini Review. Waste Manag. Res. J. A Sustain. Circ. Econ. 2019, 37, 112–119. [Google Scholar] [CrossRef] [PubMed]
[2] Niinimäki, K.; Peters, G.; Dahlbo, H.; Perry, P.; Rissanen, T.; Gwilt, A. The Environmental Price of Fast Fashion. Nat. Rev. Earth Environ. 2020, 1, 189–200. [Google Scholar] [CrossRef] [Green Version]
[3] European Parliament, Council. Directive 2008/98/EC of the European and of the Council of 19 November 2008 on Waste and Repealing Directives. 2008. Available online: http://www.fao.org/faolex/results/details/es/c/LEX-FAOC083580/ (accessed on 24 April 2021).
[4] Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of Anaerobic Digestion Process: A Review. Bioresour. Technol. 2008, 99, 4044–4064. [Google Scholar] [CrossRef] [PubMed]

[5] Apollo, S.; Onyango, M.S.; Ochieng, A. Integrated UV Photodegradation and Anaerobic Digestion of Textile Dye for Efficient Biogas Production Using Zeolite. Chem. Eng. J. 2014, 245, 241–247. [Google Scholar] [CrossRef]

[6] Gonzalez, A.; Hendriks, A.T.W.M.; van Lier, J.B.; de Kreuk, M. Pre-Treatments to Enhance the Biodegradability of Waste Activated Sludge: Elucidating the Rate Limiting Step. Biotechnol. Adv. 2018, 36, 1434–1469. [Google Scholar] [CrossRef] [Green Version]

[7] Chen, L.; Qin, Y.; Chen, B.; Wu, C.; Zheng, S.; Chen, R.; Yang, S.; Yang, L.; Liu, Z. Enhancing Degradation and Biogas Production during Anaerobic Digestion of Food Waste Using Alkali Pretreatment. Environ. Res. 2020, 188, 109743. [Google Scholar] [CrossRef]

[8] Anacleto, T.M.; Oliveira, H.R.; Diniz, V.L.; de Oliveira, V.P.; Abreu, F.; Enrich-Prast, A. Boosting Manure Biogas Production with the Application of Pretreatments: A Meta-Analysis. J. Clean. Prod. 2022, 362, 132292. [Google Scholar] [CrossRef]

[9] Prabakar, D.; Manimudi, V.T.; Mathimani, T.; Kumar, G.; Rene, E.R.; Pugazhendhi, A. Pretreatment Technologies for Industrial Effluents: Critical Review on Bioenergy Production and Environmental Concerns. J. Environ. Manag. 2018, 218, 165–180. [Google Scholar] [CrossRef]

[10] Mustafa, A.M.; Poulsen, T.G.; Xia, Y.; Sheng, K. Combinations of Fungal and Milling Pretreatments for Enhancing Rice Straw Biogas Production during Solid-State Anaerobic Digestion. Bioresour. Technol. 2017, 224, 174–182. [Google Scholar] [CrossRef] [PubMed]

[11] Orlando, M.Q.; Borja, V.M. Pretreatment of Animal Manure Biomass to Improve Biogas Production: A Review. Energies 2020, 13, 3573. [Google Scholar] [CrossRef]

[12] Abraham, A.; Mathew, A.K.; Park, H.; Choi, O.; Sindhu, R.; Parameswaran, B.; Pandey, A.; Park, J.H.; Sang, B.I. Pretreatment Strategies for Enhanced Biogas Production from Lignocellulosic Biomass. Bioresour. Technol. 2020, 301, 122725. [Google Scholar] [CrossRef] [PubMed]

[13] Amin, F.R.; Khalid, H.; Zhang, H.; Rahman, S.; Zhang, R.; Liu, G.; Chen, C. Pretreatment Methods of Lignocellulosic Biomass for Anaerobic Digestion. AMB Express 2017, 7, 72. [Google Scholar] [CrossRef] [Green Version]

[14] Pellera, F.M.; Santori, S.; Pomi, R.; Polettini, A.; Gidarakos, E. Effect of Alkaline Pretreatment on Anaerobic Digestion of Olive Mill Solid Waste. Waste Manag. 2016, 58, 160–168. [Google Scholar] [CrossRef]

[15] Thompson, T.M.; Young, B.R.; Baroutian, S. Advances in the Pretreatment of Brown Macroalgae for Biogas Production. Fuel Process. Technol. 2019, 195, 106151. [Google Scholar] [CrossRef]

[16] Montgomery, L.F.R.; Bochmann, G. Pretreatment of Feedstock for Enhanced Biogas Production. IEA Bioenergy 2014. Available online: https://www.ieabioenergy.com/wp-content/uploads/2014/02/pretreatment_web.pdf (accessed on 13 November 2021).

[17] Brémond, U.; de Buyer, R.; Steyer, J.P.; Bernet, N.; Carrere, H. Biological Pretreatments of Biomass for Improving Biogas Production: An Overview from Lab Scale to Full-Scale. Renew. Sustain. Energy Rev. 2018, 90, 583–604. [Google Scholar] [CrossRef]

[18] B. Wu, E.L. Bibeau et K.G. Gebremedhin, Three-dimensional numerical simulation model of biogas production for anaerobic digesters, CANADIAN BIOSYSTEMS ENGINEERING, volume 51, 2009.

[19] L. Jürgensen, E. A. Ehimen, J. Born et J. B. Holm-Nielsen, Dynamic biogas upgrading based on the Sabatier process: Thermodynamic and dynamic process simulation, Bioresource Technology, pages, 2014.

[20] M. Lubken, M. Wichern, M. Schlattmann, A. Gronauer et H. Horn, Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops, WATER RESEARCH, volume 4, pages 4085 – 4096, 2007.

[21] K. G. Gebremedhin, Biogas Production Model for Plug-Flow Anaerobic Digesters, ASABE Annual International Meeting, 2006.

[22] D. T. Hill et C. L. Barth, A Dynamic Model for Simulation of Animal Waste Digestion, Water Pollution Control Federation, volu me 49, pages 2129-2143, 1977.

[23] A. Sokolenko, O. Shevchenko, I. Maksymenko, K. Vasylkivskyi, Energy transformations in processes of anaerobic fermentation, Ukrainian Food Journal, volume 7, pages 273-280, 2018.

[24] K. Opwis, T. Mayer-Gall, J. S Gutmann, C. Dammer, T. Titscher, A. Nickisch-Hartfiel, O. Grün, C. Spurk, C. Schloderer, A. Köppe, C. Dörfler et H. Bachus, Semi-industrial production of methane from textile wastewaters, Energy, Sustainability and Society, volume 2, pages 1 -6, 2012.

[25] K. Rajendran, S. Aslanzadeh, F. Johansson et M. J. Taherzadeh, Experimental and economical evaluation of a novel biogas digester, Energy Conversion and Management, volume 74, pages 183–191, 2013.

[26] J. Guo, R. Dong, J. Clemens et W. Wang, Thermal modelling of the completely stirred anaerobic reactor treating pig manure at low range of mesophilic conditions, Journal of Environmental Management, volume 127, pages 18-22, 2013.

[27] C. M. Galanakis, C. Kordulis, M. Kanellaki, A.A. Koutinas, A. Bekatorou et A. Lycourghiotis, Effect of pressure and temperature on alcoholic fermentation by Saccharomyces cerevisiae immobilized on c-alumina pellets, Bioresource Technology, volume 114, pages 492–498, 2012.

[28] A. Jeihanipour, K. Karimi, C. Niklasson, M.J. Taherzadeh,A novel process for ethanol or biogas production from cellulose in blended-fibers waste textiles Waste Management, 30 (2010), pp. 2504-2509

[29] A. Jeihanipour, K. Karimi, M.J. Taherzadeh,Enhancement of ethanol and biogas production from high-crystalline cellulose by different modes of NMO pretreatment,Biotechnology and Bioengineering, 105 (2010), pp. 469-476

[30] K. Rajendran, G. Balasubramanian;High rate biogas production from waste textiles.School of Engineering, University of Borås, Borås (2011)

[31] López-Jiménez, P.A., Escudero-González, J., Martínez, T.M., Montanana, V.F., Gualtieri, C.: Application of CFD methods to an anaerobic digester: the case of Ontinyent WWTP, Valencia, Spain. J. Water Process Eng. 7, 131–140 (2015).

[32] Wu, B., Bibeau, E.L.: Development of 3-D anaerobic digester heat transfer model for cold weather applications. Trans. ASABE 49, 749–757 (2006).