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Design of a Biogas Power Plant That Uses Olive Tree Pruning and Olive Kernels in Achaia, Western Greece

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Abstract: In Greece, agricultural residues form a significant part of available biomass resources. This study focuses on exploring energy production potential from olive tree pruning and kernels via anaerobic digestion in the Achaia region of Western Greece. It aims to address environmental challenges by analyzing anaerobic digestion of these residues. The study evaluates qualitative and quantitative attributes, including composition analysis and energy content assessment. Detailed design considerations for an anaerobic digestion system tailored for these residues are presented, laying the groundwork for practical implementation. By integrating scientific analysis with engineering principles, this research aims to optimize anaerobic digestion systems for a more sustainable agricultural landscape in Greece.

Keywords: agricultural residues; residues; anaerobic digestion; biogas; olive kernel wastes

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1. Introduction

In the scientific community, there is widespread recognition that the significant increase in anthropogenic greenhouse gas concentrations, resulting from extensive fossil fuel usage in recent decades, has led to substantial changes in the global climate system [1,2]. Additionally, concerns about the sustainability of energy sources, specifically the future availability of non-renewable fossil fuels, have given rise to significant public apprehension. Conversely, renewable energy sources (RESs) encompass a diverse range of physicochemical and biological processes that can be harnessed for energy production. These sources aim to reduce greenhouse gas emissions, diversify energy supply, reduce dependence on fossil fuel markets, and promote energy independence in small and medium-sized communities [3].

As highlighted by Østergaard et al. [4], significant progress has been made in the development of renewable energy systems, including technological innovations, resource assessment methodologies, and system design considerations. One of the prominent RESs used on a large scale is biomass, primarily due to its significant energy potential. Organic materials in the form of biomass possess the potential to transform into different energy types—gaseous and liquid fuels—capable of being stored, transported, and utilized over long distances [5].

The utilization of biomass, whether through thermal or biological conversion processes, plays a crucial role in achieving the European Union's environmental and energy objectives. When biomass is used for energy production, it does not significantly increase atmospheric CO_2 levels, as it has already sequestered a similar or greater amount of CO_2 during its life cycle. At the EU level, according to recent findings from a comprehensive JRC biomass study encompassing land-based sectors like agriculture and forestry, the estimated production of biomass in dry matter stands at around 1.466 billion metric tons annually. This comprises approximately 1000 million metric tons from agriculture and 510 million metric tons from forestry, as detailed in the study's assessment of biomass production and utilization in various sectors across the EU [6].

According to a recent commission report on bioenergy sustainability and the 2023 State of the Energy Union Report, energy production from biomass within the EU-27 has notably increased by 13% over the past decade. This surge has predominantly been propelled by significant expansions in the power and heating sectors. In 2021, biomass played a substantial role, constituting approximately 15% of total gross renewable electricity and 6% of the overall gross electricity produced, reflecting a notable rise from previous years. Moreover, in 2019, biomass accounted for nearly 19% of heat production and approximately 3% of total electricity generation across the EU [7]. While Greece possesses considerable biomass potential, the country manages biomass waste in an unregulated manner, often leading to its disposal in the environment or within landfills. This practice persists despite the availability of advanced facilities and legal frameworks [8].

Greece's extensive agricultural activities, which cover approximately 70% of the country's land area, highlight its high biomass potential. However, Greece currently does not fully exploit its biomass resources for electricity generation, leading to inadequate management of agricultural residues and adverse environmental consequences.

In this context, the Achaia region in Greece stands out for its accumulation of biomass residues. Achaia is known for its extensive olive cultivation, covering an area of 190,754 acres, featuring 3,550,518 olive trees, and producing approximately 77,580 metric tons of olive fruit annually [9].

The olive oil production in Achaia is facilitated by 44 local two-phase processing olive mills, 40 three-phase processing olive mills, 4 mills that incorporate both technologies, and 1 traditional olive mill. These mills generate an annual average of 75,580 cubic meters of liquid waste, 3103 metric tons of leaves (4% of the olive fruit), and 15,904 metric tons of olive kernel (20.5% of the olive pomace) [10]. Aside from these remnants, there is a considerable amount of leaves and small twigs resulting from pruning activities, excluding logs and timber typically set aside for household use. Among these residual materials, the focus is on those not suitable for high-value products, specifically the olive kernel and pruning-derived leaf material. Together, they represent a substantial yearly volume destined for energy and compost production. This highlights the significant agricultural residues generated in the Achaia region and underscores the untapped potential for their effective utilization in sustainable and environmentally responsible practices [11].

Olive leaves have a complex chemical composition influenced by various factors, including olive variety, climate conditions, tree age, harvest timing, and the presence or absence of agricultural inputs such as insecticides and fertilizers. Olive leaves are known to contain significant concentrations of polyphenols, which are bioactive compounds exceeding the levels found in olive oil. These polyphenols have promising applications in the food, pharmaceutical, and cosmetic industries. Furthermore, olive leaves are rich sources of trace elements, minerals, and vitamins, making them nutritionally valuable for human consumption [12]. In addition to their conventional use as field fertilizers, olive leaves have the potential to serve as cost-effective alternatives to other cultivated plants traditionally harvested for similar purposes [13].

Greece faces a knowledge gap, not only among farmers but also within industries and the general public, regarding the potential of energy recovery from biomass waste, its end-use applications, and associated advantages. Although anaerobic digestion is predominantly used as a waste management approach in Greece, it is not yet accompanied by biogas and energy production. The country's energy demands heavily rely on fossil fuels, particularly local lignite, imported petroleum, and natural gas. Approximately 61% of the nation's energy requirements are met through fuel imports, with the remainder sourced from lignite (77%) and RESs (22%), including large-scale hydropower. Presently, the cumulative installed capacity of active electricity-producing biogas plants in Greece is 33.5 MW, with licenses granted for an additional 146.5 MW.

In most applications, biogas is employed as a fuel for internal combustion engines. However, electricity production from biogas can be highly efficient if the heat generated during the power generation process is utilized in an economically and environmentally sustainable manner. The average calorific value of biogas falls within the range of 21 to 24.5 megajoules per cubic meter, equivalent to 0.5 to 0.6 L of diesel fuel or approximately 6 kilowatt-hours of energy. However, due to conversion losses, 1 cubic meter of biogas can effectively be converted to around 2.2 kWh of electricity. Typically, biogas plants achieve operational efficiencies of approximately 39% for electricity generation and 41% for thermal applications [14].

Within this paper's scope, we delve into the process of anaerobic digestion involving olive kernel and leaves sourced from olive fruit pruning raw material, elucidating its potential applications and environmental implications. Olive kernel's role as a domestic energy resource in Greece, marked by its cost-effectiveness in relation to energy yield, reduces the country's reliance on imported conventional fuels, aligning with sustainable and environmentally responsible practices. This comprehensive perspective underscores the multifaceted benefits and versatile applications of olive kernel within the Greek context, positioning it as a valuable asset for energy production and soil enhancement, ultimately contributing to economic self-sufficiency and environmental preservation. The innovation of our work is exactly the proposal for exploitation of this Achaia-oriented material, otherwise suggested as waste, to produce energy. This idea allows for more efficient olive tree cultivation and olive oil production, increasing the local potential for sustainability.

In this study, we aim to address the knowledge gap in Greece regarding the potential of energy recovery from biomass waste, covering farmers, industries, and the general public. Our goal is to illuminate the possibilities of biomass waste utilization, explore its diverse applications, and emphasize the associated benefits, both from an environmental and energy security perspective.

2. Anaerobic Digestion Process Overview

Anaerobic digestion stands as a fundamental bioconversion process critical for the transformation of organic substrates under anaerobic conditions. Orchestrated by a diverse consortium of microorganisms, this controlled degradation yields stabilized organic residues and biogas—a predominantly methane and carbon dioxide-based sustainable energy source [15]. Predominantly occurring in liquid phases, anaerobic digestion excels in substrates characterized by low solid concentrations and high moisture content, typically within the range of 60% to 95%. Despite its relatively lower metabolic rate in comparison to aerobic digestion, the process demonstrates substantial efficiency. The successful breakdown of lignocellulosic materials, influenced significantly by material porosity, cellulose crystallinity, and lignin content, is pivotal for effective digestion. Strategies involving innovative pretreatment methodologies aim to enhance cellulose conversion efficiency [16].

At the forefront of anaerobic digestion, hydrolysis acts as a pivotal initial phase, converting complex and insoluble organic compounds into accessible substrates suitable for bacterial assimilation. However, certain recalcitrant organic materials pose challenges due to their structural complexity and resilient chemical bonds [17,18].

Advancing from hydrolysis, the oxygenesis phase facilitates the transformation of hydrolytic products into smaller organic acids like propionic and butyric acids. Unlike subsequent stabilization phases, oxygenesis primarily alters organic material independently, functioning without reliance on external electron acceptors [19,20].

Subsequent to oxygenesis, acidogenesis extends the conversion process, yielding a spectrum of compounds encompassing acetic acid, H_2, CO_2, and various organic acids. The maintenance of low hydrogen levels becomes imperative for efficient methane generation—a hallmark of proficient anaerobic digestion [20,21].

The final stage, methanogenesis, involves specialized bacteria thriving in anaerobic conditions. These microorganisms metabolize compounds such as acetic acid, CO_2, and H_2, culminating in methane production. The activity of methanogenic bacteria is significantly influenced by environmental factors, including temperature, pH, nutrient availability, and the presence of toxic substances [17,21].

In summation, the efficacy of anaerobic digestion is intricately tied to environmental parameters, including temperature, pH, nutrient availability, and toxicity. Prudent management of these variables not only optimizes biogas production but also ensures the seamless operation of the entire system. Recent advancements in anaerobic digestion methodologies, coupled with their pivotal roles in waste management, renewable energy production, and environmental sustainability, reaffirm their enduring significance in contemporary scientific and practical realms.

3. Methodology of Anaerobic Digestion System Design

The design methodology of this study follows a sequential application of specific criteria that are essential for various components, including unit capacity, biomass storage tank volume, characteristics of the digestion tank, hydraulic retention time (HRT) and digester capacity, preheating biomass procedure, digestion tank heating, calculation of digested sludge, storage calculation of digested sludge, biogas storage system, and lastly, the burning torch. The Figure 1 depicts the abovementioned design methodology.

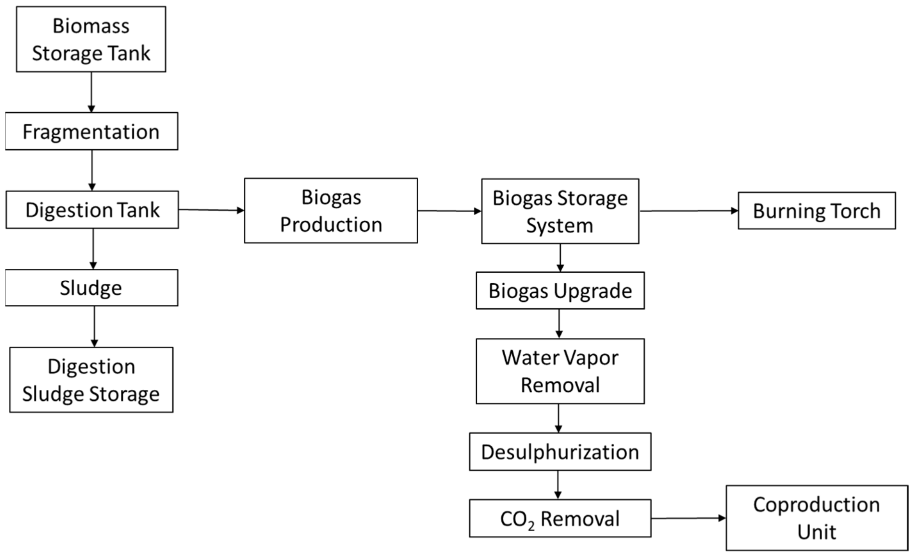

Figure 1. Schematic representation of the anaerobic digestion system design.

3.1. Unit Capacity

The total biomass produced in Achaia from pruning and olive kernel leaves amounts to 35,432 tons. This production occurs during the four months of operation (November–February = 120 days) of the olive mills and olive kernel mills. Assuming an equal daily allocation of production, the daily biomass production reaches 295 tons per day. In the case that the anaerobic digestion unit operates for 11 months or 330 days (with 1 month allocated for maintenance works), the daily biomass production amounts to 107.37 tons per day or 4.47 tons per hour.

For every 1 kg of dry material (olive kernel), 0.5 m^3 of biogas is produced [22]. Considering that the total average moisture content (olive kernel and olive leaves) is 60% and the thermogenic power of biogas is 6.5 kWh/m^3, the hourly production of biogas is 894 m^3/h, with a power output of 5811 kW. To calculate the unit capacity after upgrading biogas to biomethane, we assume that the biogas contains 65% CH_4 [23] and the thermogenic power of biomethane is 10.5 kWh/m^3. Consequently, the thermogenic power of biomethane is 6101 kW and the hourly production of biomethane is 581 m^3/h. The summarized unit capacity data, as calculated by using the abovementioned approach, are depicted in Table 1.

Table 1. Summarized unit capacity data.

Olive Kernel and Leaves from Pruning	4.47 tons/h
Biogas Supply	894 m^3/h
Biogas Power	5.81 MW
Biomethane Production	581 m^3/h
Biomethane Power	6.1 MW

3.2. Biomass Storage Tank Volume

The storage of biomass primarily serves to compensate for its seasonal fluctuations and enables the blending of various homogeneous substrates for continuous use in the digester. To facilitate this process, a silo-type storage tank made from galvanized steel is employed. The tank is equipped with agitators that incorporate tearing and cutting tools, which are designed to break down the biomass into small pieces, typically ranging from 2 to 5 mm in size. This fragmentation not only eases the mixing process but also prepares the surfaces of the biomass for biological decomposition and subsequent biogas production. It is worth noting that particles of smaller size lead to faster decomposition, although they may not necessarily result in increased CH_4 production. Calculations are depicted in Table 2.

Table 2. Biomass storage tank volume calculations.

Daily Biomass Production	295 tons/day
Required biomass (11-month operation)	107.37 tons/day
Difference (added daily during 4-month operation)	188 tons/day
Biomass density	0.75 tons/m^3
Safety factor	10%
Storage tank volume	18,612 m^3

3.3. Characteristics of the Digestion Tank

Figure 2 illustrates the algorithm employed for choosing the digestion tank in a flowchart format.

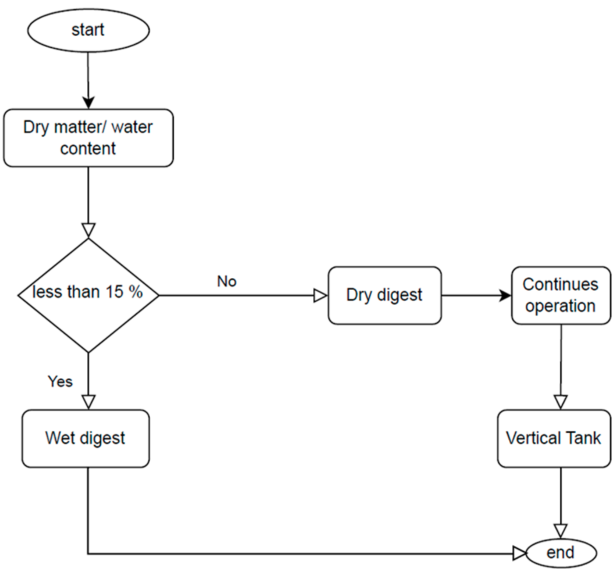

Figure 2. Selection of the digestion tank.

The vertical design is the most common choice for ensuring continuous operation in anaerobic digestion systems. This design allows for the continuous feeding of biomass, enabling the simultaneous introduction of new biomass while mechanically extracting the digested material. This arrangement facilitates uninterrupted biogas production and is often preferred for its efficiency in maintaining a consistent and reliable process [24]. The digester is constructed with a concrete base and a steel structure, and its interior is insulated with waterproof polystyrene insulation plates. This construction method is chosen to protect the digester from corrosion and maintain proper insulation. The digester is designed to be fully mixed to achieve the homogenization of the biomass and enhance biogas production.

Maintaining a consistent process temperature is crucial for stable operation and high biogas production efficiency. To achieve this, the biomass is preheated during feeding using heat exchangers. Additionally, a system of stainless-steel hot water circulation pipes is installed inside the digester to ensure that it operates at a mesophilic temperature of 35 °C. This temperature range is chosen to avoid both the psychrophilic (T < 20 °C) and thermophilic (T > 45 °C) regions, where biological reaction rates are reduced due to the limited adaptation of microorganisms. By maintaining this temperature range, the system optimizes the performance of anaerobic digestion [25].

3.4. Hydraulic Retention Time and Digester Capacity

Hydraulic retention time refers to the duration during which the material available for digestion remains within the digester, allowing anaerobic microorganisms to complete their cell cycle. In the context of this biomass digestion system, the HRT is a critical factor for achieving efficient biogas production. According to Boubaker and Ridha [26], optimal performance in terms of CH_4 production is achieved with a hydraulic retention time of 12 days for waste generated by olive mills, encompassing both liquid and solid components. In addition to this literature estimate, the HRT can also be mathematically calculated using an appropriate formula:

$$\Theta_{opt} = \frac{1-K}{\mu_M} + \left\{ \frac{K B_0 \; HHV_{MET} \; VS}{86,400 \; \mu_M \left\{ \frac{K_{VR} \, (T_R - T_F)}{n_\theta} + \frac{W_{AR}}{n_E} \right\}} \right\}^{1/2}, \quad (1)$$

where K = 0.33 is the kinetic parameter of anaerobic digestion [27] and $\mu_M = 0.326$ is the maximum growth rate of microorganisms, which increases with temperature. Given the temperature range 30–60 °C, the value of $\mu_M = 0.013T_R - 0.129$ (1/day), where μ_M represents the specific methane production rate. This rate is influenced by factors such as the operating temperature of the digestion tank (T_R = 35 °C), the mean environmental temperature (T_F = 18 °C), and the degree of conversion of biogas into heat ($n_\theta = 0.85$). With B_o = 0.25 Nm^3/kg VS is denoted the maximum methane production for a given substrate in this case. It signifies the superior thermogenic power of the substrate, which contains volatile solids at a concentration of VS = 96 kg/m^3 in glucose equivalent, $HHV_{MET} = 3.4 \times 10^7$ J/m^3 stands for the high heating value of methane, which is a critical parameter in the biogas production process, K_{VR} = 0.453 W/m^3 K represents a volumetric loss factor used in the equation, derived from the loss factor (that accounts for factors like heat transfer and insulation) and the dimensions of the digestion tank. Additionally, there are factors such as W_{AR} = 34.38 W/m^3, which signifies the degree of stirring per digestion tank volume (w/m^3), and n_E = 0.35, which represents the degree of conversion of biogas into electricity.

In summary, the equation relates various parameters and factors affecting the specific methane production rate in a biogas system, including temperature, substrate properties, thermogenic power, heating values, and conversion efficiency into heat and electricity.

The optimal residence time, calculated to be 19 days, is a crucial parameter for the efficient operation of the anaerobic digestion system. This residence time ensures that anaerobic microorganisms have sufficient time to complete their cell cycles and maximize biogas production. With this residence time in mind, the digester capacity can be calculated as follows:

$$Digester\ Capacity = \frac{(Daily\ Biomass\ Production * Optimal\ Residence\ Time)}{Biomass\ DensityDigester\ Capacity} = \frac{(107.37\ \text{tones/day} * 19\ d)}{0.75\ \text{tones/m}^3} = 2619\ \text{m}^3$$

3.5. Preheating Biomass

The required biomass preheating temperature in the operation temperature T_R = 35 °C, the digestion tank's operating temperature, is calculated from the relation:

$$Q_{req} = mC_p\Delta T, \quad (2)$$

where m = 4.47 tons/h and C_p = 1.6 KJ/Kg K, the specific heat capacity of biomass [28]. Finally, the average/mean temperature ΔT of the environment in which the biomass is situated before it enters the digester is T_F = 18 °C, corresponding to Q_{req} = 33.7 KW. Assuming that the efficiency of the exchanger is n = 0.9, we can calculate the necessary heat for supplying the preheating system as Q_{req} = 33.7 KW/0.9 = 37.5 KW.

3.6. Digestion Tank Heating

To cover the heat loss to the environment, heat supply is required in order to assure a constant temperature of 35 °C. These losses depended on the area of the digestion tank surface and the thermal permeability of the digestion tank material, and are expressed as follows:

$$Q = U\ A\ (T_R - T_F), \quad (3)$$

where T_R = planning temperature = 35 °C, T_F = environment temperature=18 °C, A = the area of the lateral surface and the bases of the digestion tank, and U = 0.68 J/s m^2 °C, the thermal permeability of the digestion tank material (steel anaerobic cylindrical digestion tank) with an airtight storage system of continuous operation [29]. In accordance, calculations provide Q = 12.70 KW while it increased to Q = 14.11 KW by considering an efficiency of n = 0.9.

3.7. Calculation of Digested Sludge

By applying a simple mass balance in the digester, we get:

$$m_{in} = m_{biogas} + m_{digester}, \quad (4)$$

where m_{in} is the supply of biomass to the digestion tank (4.47 tones/h, 60% H_2O, 3.5% ash 2.5–4.5% by weight and organic material), m_{biogas} is the supply of biogas = 1028.1 kg/h or 24,674.4 kg/day, which is calculated from the volume flow, 894 m^3/h and the biogas density 1.15 kg/m^3 and $m_{digested}$ = 3442 kg/h or 82,608 kg/day (organic material − biogas) + H_2O supply + ash supply kg/h that result from the processing.

3.8. Storage Calculation of Digested Sludge

The digested substrate will be transported and temporarily stored in a cylindrical concrete tank, which will be covered with sunlight-resistant PVC material to prevent evaporation, release of odors, and the intake of rainwater. The liquid residue can be directly used as liquid organic fertilizer on the fields without the need for further processing. In compliance with both Greek and European regulations, a storage capacity of 6 to 9 months is required to ensure the optimal and efficient use of the compost as fertilizer. The storage sludge capacity is calculated to be 19,826 m^3, assuming a tank height of 12 m and a tank radius of 23 m to accommodate this capacity.

3.9. Biogas Storage System

Inside the digester, biogas production can exhibit fluctuations with performance peaks, and the demand for biogas in a co-production unit may vary. To address these variations, it is necessary to have temporary storage facilities for biogas. Therefore, a double-membrane system is chosen as an external repository capable of storing the maximum biogas production within 2 h. This system will have a capacity of approximately 894 $m^3/h \times 2$ h= 1788 m^3.

The outer membrane is designed to be durable, resistant to weather conditions, and impervious to the sun's ultraviolet rays, while also providing protection for the inner membrane against wind and environmental factors. The inner membrane is constructed from plastic material based on polyester fibers, specially designed for biogas storage. This design ensures the efficient and reliable storage of biogas to accommodate varying production and demand patterns.

3.10. Burning Torch

Storing biogas for extended periods can indeed be challenging due to its large volume. While short-term storage without compression is feasible, long-term storage becomes more problematic. When excess biogas cannot be effectively stored or used, a burning torch or flare system is a common and safe solution for disposal. In this case, the burning torch is designed with a capacity of 1000 m^3/h, allowing it to burn the amount of biogas produced in one hour. The relevant data and values are summarized in Table 3 for reference.

Table 3. Data and values for the anaerobic digestion system design.

Data	Values
Unit Capacity	4.47 tons/h
Biomass Production (Daily)	107.37 tons/day
Biogas Production (Hourly)	894 m^3/h
Biogas Power Output	5811 kW
Biomethane Power Output	6101 kW
Biomethane Production (Hourly)	581 m^3/h
Biomass Storage Tank Volume	18,612 m^3
Digestion Tank Type	Vertical
Digestion Tank Insulation	Polystyrene
Process Temperature (Mesophilic)	35 °C
HRT	19 days
Digester Capacity	2619 m^3
Biomass Preheating Requirement	33.7 kW
Digestion Tank Heat Loss	12.70 kW
Digested Sludge Composition	Varies
Digested Sludge Storage Capacity	19,826 m^3
Biogas Storage System	Double Membrane
Biogas Storage Capacity	1788 m^3
Burning Torch Capacity	1000 m^3/h

4. Biogas Upgrade

The biogas when leaving the digestion tank is saturated in water vapor (relative humidity 100%) and contains CH_4-CO_2 and an amount of H_2S. All the above are considered as wastes that must be removed to avoid the H_2SO_4 formation and to protect the coproduction unit.

4.1. Water Vapor Removal

The biogas enters the upgrading unit at a pressure considerably lower than the atmospheric one. It is then compressed to a pressure of 6 bar, thus resulting in a temperature rise to 85 °C. The biogas undergoes gradual cooling until it reaches 6 °C to produce dry biogas, after which it is reheated to 45 °C before being transported to the desulfurization unit. The energy needed for cooling or heating in these conversions is calculated using generalized Equation (2), where the specific heat capacity at constant pressure is calculated by using the values Cp_{CH4} = 2.22 KJ/Kg K, Cp_{CO2} = 0.844 KJ/Kg K, Cp_{H2O} = 1.93 KJ/Kg K, Cp_{N2} = 1.04 KJ/Kg K, Cp_{biogas} = $0.65Cp_{CH4}$ + 0.30 Cp_{CO2} + $0.03Cp_{H2O}$ + $0.02Cp_{N2}$ = 1.77 KJ/Kg K, m_{biogas} =1028.1 Kg/h, (894 m^3/h × 1.15 Kg/m^3), $Q_{cooling}$ = 40 KW, [(1028.1 Kg/h × 1.77 KJ/Kg K × 79 K)]/3600 KJ, $Q_{heating}$ = 20 KW, and [(1028.1 Kg/h × 1.77 KJ/Kg K × 39 K)]/3600 KJ. Again, the dimensioning of the unit corresponds to a maximum power of 40 KW.

4.2. Desulfurization

Maintaining low levels of hydrogen sulfide is crucial for the use of biogas in gas engines for combined heat and electricity production. H_2S levels should be kept below 700 ppm to prevent excessive corrosion of the equipment. The desired level of desulfurization can be achieved through both internal processes within the digester and external procedures during biogas upgrading [30].

Internal desulfurization involves the presence of oxygen and oxidizing sulfobacteria within the digester. These microorganisms convert H_2S into H_2SO_4 (sulfuric acid) and later into elemental sulfur. The elemental sulfur is carried with the sludge and water. Oxidative sulfobacteria are naturally present due to the nutrients available in the anaerobic digestion substrate. Oxygen is introduced into the digester by injecting air from the side opposite to the biogas extraction to prevent any obstruction of the extraction pipe.

External desulfurization uses a dry biogas that is passed through an activated carbon filter at around 5 bar pressure. This process effectively removes H_2S from the biogas. The H_2S is absorbed by the carbon filter and transformed into elemental sulfur. To maintain the filter's efficiency, it typically needs replacing every two years for optimal performance. To enhance the filter's efficiency, a small amount of air is introduced into the biogas. This selection of a biogas compressor is based on the maximum biogas production of 894 m^3/h.

These desulfurization processes ensure that the biogas is of suitable quality for utilization in gas engines for combined heat and power production (CHP), preventing equipment corrosion and ensuring a clean and reliable energy source.

4.3. CO_2 Removal

The chosen technology for CO_2 removal is the pressure swing adsorption (PSA) method. This system consists of twelve pressure exchange vessels filled with activated carbon, which serve as a "molecular sieve." The CO_2 removal process involves the following steps:

1. Biogas enters from the bottom of the vessel.
2. The gas is compressed to 5 bar.
3. Methane molecules pass through the "molecular sieve," resulting in a high-CH_4-content gas that exits from the top of the container.
4. Carbon dioxide molecules are trapped within the molecular sieve and are released when the pressure is reduced. This produces a CO_2-rich gas that exits from the bottom of the vessel.

The unit comprises twelve vessels operating in three phases. In each phase, four vessels are in a pressure increase phase, four are at high pressure (producing biomethane), and four are in a pressure-decrease phase (producing the CO_2 stream). This design ensures a consistent production of biomethane. Each set of four containers takes approximately 460 s to complete a compression–production–expansion cycle. The CH_4 percentage is continuously monitored, and if it falls outside the specifications, the produced gas is redirected back into the PSA system. The unit has a maximum capacity of 600 m^3/h with a CH_4 percentage of 97%. This capacity is determined by the digester's ability to produce biogas [30]. The electrical consumption of the PSA system for CO_2 removal is 0.2 kWh/Nm^3 [31]. Therefore, the required power for the entire biogas supply (894 m^3/h) is 179 kW.

This CO_2 removal process ensures the production of high-quality biomethane suitable for various applications. The relevant sections and their descriptions are summarized in Table 4.

Table 4. Biogas update process.

Section	Description
Biogas Upgrade	The process of enhancing biogas quality
Water Vapor Removal	Removal of water vapor from biogas
Method	Compression, cooling and reheating
Cooling Energy ($Q_{cooling}$)	40 KW
Heating Energy ($Q_{heating}$)	20 KW
Desulfurization	Removal of H_2S from biogas
Internal Desulfurization	Using oxidative sulfobacteria and oxygen
External Desulfurization	Dry biogas passed through an activated carbon filter
Biogas Compressor	Selected based on a maximum production of 894 m^3/h
CO_2 Removal	Removal of CO_2 from biogas
Method	PSA method
Number of Vessels	Twelve vessels operating in three phases
Electrical Consumption	0.2 kWh/Nm^3
Required Power for the PSA System	179.0 kW

5. Co-Production Unit

The CHP unit is designed to fulfill the thermal and electrical requirements of the biomass processing unit, while any surplus energy produced can be supplied to relevant stakeholders. The calculation for the CHP's final production is based on the maximum flow rate of biomethane (equal to 13,944 m^3 per day or 581 m^3 per hour). The efficiency of the CHP system is taken into consideration, with the internal combustion engine having an efficiency of 93% and the generator's efficiency is 95.26%, as specified by the manufacturer.

The total energy production is given by the formula:

$$Q + W = 0.93\ (6.1\ \text{MW}) = 5.67\ \text{MW}, \tag{5}$$

where Q is the heat, W is the electricity produced, and 6.1 MW is the power of the biomethane supplied to the CHP.

The electricity-to-heat ratio (PHR) is defined by the formula:

$$PHR = \frac{W}{Q} = \frac{n_e}{m_{th}}, \tag{6}$$

which is also expressed as a function of electrical and thermal efficiency, n_e and m_{th}, respectively [32]. According to the manufacturer's technical specifications, PHR = (0.43/0.419) = 1.03.

The CHP system produces 2.79 MW of heat and 2.88 MW of electricity. However, considering the generator's efficiency of 95.26%, the actual generated electricity is 2.74 MW. As a result, the CHP system operates with an efficiency of 45.74% for thermal energy and 47.2% for electrical energy. Considering the total energy requirements of the anaerobic digestion plant (approx. 769 KW of electricity and 197 KW of thermal energy), the net production available for use is 1971 MW of electricity and 2593 MW of thermal energy.

6. Discussion

Findings from a study by Sansoucy [33] indicate that the concentration of phenols tends to decrease in dry olive leaves, with a reduction of approximately 36% compared to their fresh counterparts. Upon conducting comparative analyses between fresh and olive leaves dried at 60 °C, the discernment of their respective chemical compositions was facilitated [34], as shown in Table 5. These data emphasize the versatile and valuable chemical composition of olive leaves, highlighting their potential applications in various industries and agricultural practices.

Table 5. Chemical composition of olive leaves in powder form dried at 60 °C and fresh olive leaves.

Components	Dried 60 °C Olive Leaves (g/kg DM)	Fresh Olive Leaves (g/kg DM)
Organic matter	861	870
Gross energy (MJ/kg DM)	19.9	20
Ether extract	78.1	97.6
Total nitrogen	11.3	11.4
Acid detergent fiber	270	267
Acid detergent insoluble nitrogen (g/g total nitrogen)	0.595	0.509
Sulfuric acid lignin	163	158
Tannins (total)	6.24	10

The production of olive kernel follows a well-defined process that initiates with the initial processing of olive fruit in olive mills to extract olive oil and olive pomace. Olive pomace, characterized by its elevated moisture content, comprises the remnants of olive pits and flesh remaining after the initial crushing. Following this, the olive pomace undergoes further processing in kernel oil mills, where the olive kernel is separated from the residual flesh remnants generated in the previous stage. This process results in two distinct categories of kernel oil: first-quality (flesh) and second-quality (kernel) kernel oil, with olive kernel emerging as the primary by-product [35]. The main characteristics of oil kernel are depicted in Table 6.

Table 6. The main characteristics of olive kernel [35].

Components	Content (g/100g Dry Weight)
Carbon	49.7–50.1
Hydrogen	6.0–7.0
Nitrogen	1.1–1.6
Sulfur	0.01–0.08
Oxygen	38.1–38.8
Moisture	12.0–15.0
Specific Weight (kg/m^3)	720.0–750.0

Olive kernel is a valuable low-cost energy resource, driven by its high calorific value, which ranges from 3500 to 4500 kcal per kilogram, varying with olive tree variety, the stage of the olive fruit's biological cycle, and the proportion of organic matter or soil content in the kernel [36]. This impressive calorific value positions olive kernel as a significant and economically efficient energy source, suitable for heat generation and energy production, while its affordability makes it an attractive and sustainable option in the energy sector.

In addition to its significance as an energy resource, olive kernel presents compelling advantages when applied as a soil improver [37]. Despite Greece annually importing substantial volumes of compost-type soil enhancers, an extensive survey of the local compost market revealed significant variations in the quality of available products. Assessments of physical, chemical, and biological parameters showcased wide disparities, raising concerns about environmental and public health implications. Heavy-metal levels in some composts exceeded Greek standards, but fell below more stringent limits elsewhere in the EU. The presence of specific pathogens and indicators further emphasized the variability in product quality. These findings underscore an urgent necessity for Greece to establish robust quality assurance protocols. Additionally, they highlight the potential need for standardized EU compost quality standards to harmonize the market across member states [38].

The implications of this approach, supported by relevant arithmetic data, are significant, especially for the following areas:

1. Soil Improvement: The anaerobic digestion process converts a substantial number of solid residues into organic soil conditioners, totaling approximately 35,432 tons during the four months of operation of olive mills. This not only reduces waste but also enhances the overall health of agricultural soils, potentially improving crop productivity.
2. Green Energy Production: The co-production of "green energy" through anaerobic digestion is a key highlight. The process results in the production of biogas and biomethane. From 1 kg of dry material (olive kernel), approximately 0.5 m^3 of biogas is produced. With a daily biomass production rate of 107.37 tons over an eleven-month operational period, the hourly production of biomethane reaches 581 m^3/h, with a thermogenic power of approximately 6.1 MW.
3. Reduction of Air Pollution and Fossil Fuel Dependence: The biogas and biomethane generated from these processes contribute to reducing air pollution and dependence on fossil fuels. The co-production unit harnesses the energy produced, resulting in approximately 2.79 MW of thermal energy and 2.88 MW of electrical energy. The CHP system's efficiency, at 45.74% for thermal energy and 47.2% for electrical energy, reflects substantial gains in energy production while minimizing losses.
4. Sustainable Energy Generation: The total energy requirements for the anaerobic digestion plant amount to 769 kW of electricity and 197 kW of thermal energy. The resulting net production stands at 1971 kW for electricity and 2593 kW for thermal energy, emphasizing the sustainable and efficient nature of the anaerobic digestion process.

To provide a clue, this research aligns with international goals and conventions for sustainability and climate crisis mitigation, such as the United Nations' sustainable development agenda. It opens avenues for advanced technologies and further exploration, offering prospects for the Western Greece region and beyond. The findings, enriched by quantitative data, lay the foundation for future research endeavors, focusing on optimizing anaerobic digestion processes, improving resource management, and advancing technologies in the field. These avenues hold promise for ongoing innovation and the continued pursuit of sustainable energy and agriculture practices.

7. Conclusions

This study highlights significant outcomes from the utilization of olive tree pruning and kernels in anaerobic digestion, emphasizing the conversion of solid residues into a valuable soil conditioner and the generation of green energy in the form of electricity and thermal energy. The process also demonstrates a substantial reduction in air pollution and a significant step towards mitigating the climate crisis. Additionally, it presents avenues for job creation, economic growth at regional and national levels, and sets the stage for further innovative research in the Western Greece region. These findings underscore the potential of anaerobic digestion in addressing critical environmental and energy challenges while contributing to the global sustainability agenda. Future endeavors may focus on optimizing this process further and exploring expanded applications, solidifying its role in sustainable development and fostering a greener economy.

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