# Biogas Production through Co-Digestion of Olive Mill with Municipal Sewage Sludge and Cow Manure

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## ABSTRACT

The treatment of olive mill (OM) residues from agricultural facilities is a daunting challenge since tremendous amounts are disposed per annum that should be treated. One of the promising treatment methods is the anaerobic methanogenic digestion of OM residues. In current investigations, the anaerobic digestion of the OM substrate is enhanced through mixing its slurries with sewage sludge (SS) or with cow manure (C), which consists of the kernels for the digestion process. Besides feedstock, other operational parameters such as hydraulic retention time (HRT), temperature and pH have a great impact on the biogas production rate and quality. Experimental investigations were conducted by means of the anaerobic biodegradation of the substrate for OM-SS and -C using a batch reactor under mesophilic conditions and foreseen HRT for 30 days. Almost neutral pH values of 7.4-7.6 were found for the anaerobic treatment of the substrate for OM-SS, and a slightly acidic pH in the range of 4.8-5.3 was found for the anaerobic treatment of the substrate for OM-C. The results revealed that the biogas production for OM-SS and -C exceeded 0.07 and 0.31 $L_{Biogas}/(L_{Ferm}\cdot day)$, respectively. Regarding the COD reduction, its removal efficiency was obtained as 46.1 and 53.8% for OM-SS and -C respectively. For economic concerns, significant methane yields were attained as 56.8 and 115.8 [$L_{CH4}/kg_{COD}$] for the OM-SS and -C substrates, respectively. In virtue of these remarkable merits, anaerobic methanogenic digestion should be adapted to a commercial scale for the treatment and biogas production of OM residues.

## 1. INTRODUCTION

The demand for fossil fuels has been dramatically increasing in the last few decades due to the acceleration for covering the population and industrial market inquiries. Maintaining the current exhaustion rates of fossil fuels would definitely cause depletion in the current renewable sources in the coming few decades. Energy and environment are rapidly growing fields of sustainability, which are meeting the needs for future energy without compromising the livelihood of the coming generations. Energy and environmental technologies refer to the knowledge of the usage skills required for energy production and integration. Consequently, one of the options is to look for alternative sources of renewable energy. The desire for new sources of sustainable energy boosts research toward the development of new strategies and technological solutions, which might be born through the treatment of biomass residues and their conversion into biofuels. Eventually, three goals are met in this context; disposal of residues through eco-friendly practices, eliciting of new energy sources, and lowering greenhouse emissions. Most countries around the world have declared strategies to switch towards renewable energy sources away from the use of the conventional fossil fuels and nuclear power. It is incumbent upon every society to implement this imperative, to preserve energy efficiency, and

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eliminate the ecological damage that occurs through pollution and emissions.

Association of Agricultural Research Institutions in the Near East and North Africa (AARINENA) countries are suitable and thriving areas for olive trees cultivation, and constitute more than 18% of the world's olive oil production (Goncalves et al., 2012; Aquilanti et al., 2014; Gholamzadeh et al., 2016; Khdair et al., 2019). Furthermore, about 36% of the cultivated areas in Jordan are planted with olive trees where more than 150,000 tons of olive fruit are harvested annually, comprising the estimations of 22,000 tons as olive oil, 75,000 tons as olive cake, and 120,000 $m^3$ as wastewater (Al-Zboon, 2020). However, the disposal of olive mill residues poses a heavily environmental load on water resources, air quality and soil (Al-Zboon, 2017; Khdair et al., 2019). Furthermore, research in the field of biogas production, in particular, from biodegradable resources is becoming of great interest in many countries, especially those having cultivated areas with olive trees which are producing the raw materials - as a by-product - obtained from olive oil processing facilities.

The primary effective parameter on the anaerobic digestion of olive mill residues is the temperature. There are three sorts of microbes that biologically convert the organic content of the feedstock within three ranges of the implemented temperature for the methanogenic process. Psychrophilic microbes are active within a relatively lower range of temperature 10-25°C, whereas the mesophilic microbes are active within a moderate temperature range of 25-40°C. Finally, thermophilic microbes thrive within a relatively higher temperature range of 45-60°C. Psychro- and thermophilic microbes are considered disadvantageous for the methanogenic process whereas mesophilic microbes, such as Methanosaeta, become optimal for the anaerobic bio-digestion of COD in the feedstock. This is so if the temperature is kept constant within mesophilic conditions, by reducing the heat ingress from/to the surroundings, by applying thermal insulation for the digesters (Gelegenis et al., 2007; Boukchina et al., 2007; Hartati et al., 2020). Another critical parameter is the pH value for the anaerobic digestion of the feedstock. Traditionally, the pH value within the neutral range is feasible for the methanogens' activities (Athanasoulia et al., 2012; Bouknana et al., 2014; Chiavola et al., 2014; Gholamzadeh et al., 2016, Thanos et al., 2021).

Previous investigations were performed to utilize the high-potential organic content in olive residues for enhancing alternative biogas revenues. Blika et al. (2009) have performed anaerobic digestion for olive mill (OM) wastewater, including pre-thermal operation besides the biological pretreatment with the help of fungi. It was found that solids must be removed from OM waste water to enhance the biogas yield, and hence, the stabilization of the digestion operation with HRT up to 30 days. According to Blika et al. (2009), this is attributed to the possible adsorption of long-chain phenolic compounds that are perilous to methanogens' activities, and hence, inhibit the methanization process. In the sequel, it was observed that a decrease in the biogas productivity and methane yield a biogas productivity rate below 0.4 L/($L_{Ferm}$·day) with a maximal COD removal of 70%. In the study of Thanos et al. (2021), the different scenarios for the digestion process of substrates, such as poultry manure, liquid pig manure and cheese whey with OM, were investigated for optimal biogas production. Their experimental results had revealed a low biogas productivity of 0.7 (L/$L_{ferm}$·day) and an average COD removal in the range of 50-58% during the steady-state conditions.

Furthermore, in a previous study of Gelegenis et al. (2007), biogas productivity from OM was conducted experimentally by co-digesting with diluted poultry-manure (DPM) in continuous reactors, fed with mixtures of OM and DPM at various mesophilic conditions (temperature, pH and OM/DPM concentrations as expressed by the organic fraction of OM to the volatile solids). These experimental attempts had revealed that biogas productivity was slightly increased up to a limited OM/DPM concentration of a value of about 40%, after which the production was decreased. This is attributed to the inhibition of the methanization process due to the formation of phenolic compounds which are toxic for the methanogens' activities.

Based on these investigations, it could be deduced that few studies have been adapted to utilize the high-potential organic content in OM for enhancing alternative biogas revenues by mixing substrates of OM with OM-SS or even with OM-C, and using them as an inoculum to enhance the methanogenic digestion. The objective of the current work is to create a simple and comprehensive methodology to produce biogas from OM residues by mixing with the two substrates as waste sewage sludge and cow manure. The proposed approach was conducted under various operational parameters, including temperature, organic matter content, pH, and COD loading in OM. In the sequel, a process commercialization is foreseen which provides a high-valued engineering solution to enhance the OM digestion process, and hence, the elimination of OM residues' accumulation in the environment. On the other hand, this approach will help in achieving a target control on waste management and a site strategy, by reducing the expenses of OM waste treatment, and improving the socio-econmic infrastructure of the olive oil producing territorials.

## 2. METHODOLOGY

### 2.1 Experimental setup

The experimental setup is shown in Figure 1. The batch reactor is manufactured of stainless steel with a capacity of 100 L. It is equipped with a water jacket and electrical heater to maintain the necessary temperature of the digestion process. A water jacket is installed around the reactor to prevent heat loss. The stainless steel reactor is equipped with temperature and pressure gauges for monitoring the predefined parameters under which the digestion process is taken place. The feedstock is introduced to the reactor through an inflow port and filled up to about 70% of the total volume with OM while the balance of the volume is filled with the substrate of OM-SS or -C.

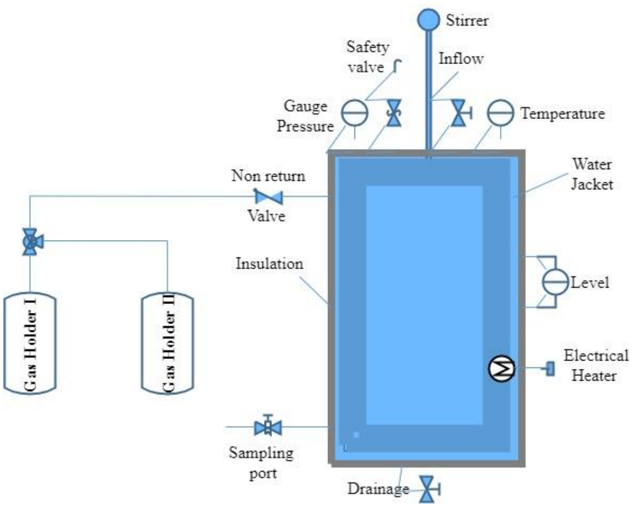


**Figure 1.** Experimental setup for biogas production for substrate digestion of OM-SS and -C

A tie-in is used as a sampling port for monitoring the produced biogas during the digestion process. The reactor is equipped with a safety valve to avoid the build-up pressure. The digestion process is run for a foreseen period of time of 30 days. According to the reviewed literature, this time period is believed to be sufficient for feedstock digestion and for establishing a stabilization stage consequently for the plant economics (Gelegenis et al., 2007; Blika et al., 2009). The produced gas is routed through a non-return valve to in-series connected gas holders. When the first one reaches a default pressure of 1 bar gauge, the produced gas is directed to the second gas holder.

### 2.2 Experimental procedure

The experimental procedure is presented as the following: the substrate of OM-SS or -C is mixed and prepared such that the reactor is filled up 70% of the total volume with OM and the balance is with SS or C. The level is regulated through a level controller. The temperature is monitored under the mesophilic conditions with an optimal value of 35±1°C while the thermal duty is regulated through the electrical heater. The water jacket ensures uniform temperature distribution through the entire batch reactor and is kept constant with the help of insulation. In order to ensure the homogeneity of the substrate mixture along the whole HRT of the digestion process, a mechanical mixer is utilized for this purpose with a constant rate of 15 times/h. Initial mixture chrematistics (pH, BOD, COD, TSS) is recorded as well as with periodical samples being withdrawn from a special sampling port and analyzed in the lab. If needed, additives such as calcium bi-carbonate are added to the reactor to maintain the pH in the applicable range, since the methanogenic digestion occurs under anaerobic conditions, which could contribute to a general acidification. The addition of such additives is repeated until a stabilization stage is established at the end of the methanogenic digestion. A percentage of 5% by volume (calcium bi-carbonate to OM mixture) was added, accordingly, an amount of 2-5 g of calcium bi-carbonate is mixed with 50 mL of OM, and then the batch reactor is buffered with the alkaline calcium bi-carbonate mixture through the inflow port. The generated gas is collected daily to determine its volume. Moreover, the substrate's temperature and pressure are measured daily. Biogas constituents are analyzed by means of gas chromatography. After the completion of each individual experimentation, the reactor is entirely drained and prepared for the upcoming investigations. The experimental data, including temperature, pH, and the gauge pressure of the reactor and the collected/accumulative gas volumes are recorded.

## 3. RESULTS AND DISCUSSION

### 3.1 Composition of the raw waste

The composition of the substrate was analyzed to get its significant constituents as shown in Table 1. Two substrates were investigated using OM-SS and -C, respectively. It is clear that the OM-C has higher concentrations of the relevant consitutents than OM-SS; this is attributed to the pretreatment of the sewage sludge in the OM-SS mixture, where the organic matter constituents TSS and TN must be dramatically reduced. The phenol content is a major concern in the methanogenic process because it is perilous when its content exceeds the limit of 4,000 PPM (Levén et al., 2012; Hartati et al., 2020), where it had been reported that phenol has a relatively faster degradation during anaerobic digestion under mesophilic conditions than the other consitutents.

### 3.2 pH profile

The pH value was maintained within the neutral range (7.4-7.6) for biogas production from the digestion process of OM-SS and -C as shown in Figure 2. The acidic pH values (pH≤7) are a sequel to the presence of high phenol constituents which are harmful for the methanogenic process. Obviously, the microbial growth for the benefit of methane production is only feasible in an OM-SS medium of almost neutral pH within the range of 7.4-7.6. The pH fluctuations are attributed to the variation of phenolic concentrations in the substrate, methanogenization of organic content, production of $CO_2$, and the formation of the acidic compounds. Regular mixing of the substrate provides sufficient homogeneity of the OM-SS medium, and consequently, the profitable dilution of phenolic compounds inside the reactor. To control the pH figures, calcium bi-carbonates are added in a scheduled manner to the reactor. This alkaline additive supports the suitable environment for better biodegradation of the perilous and long-chain phenolic compounds.

**Table 1.** Characterization of substrates for OM-SS and -C before anaerobic treatment

| Parameter | Unit | OM-SS | OM-C |
|---|---|---|---|
| | | Before | Before |
| pH | - | 5.05 | 5.00 |
| COD | PPM | 47,500 | 97,100 |
| BOD | PPM | 31,100 | 47,680 |
| TSS | PPM | 17,400 | 21,450 |
| TN | PPM | 4,105 | 30,900 |
| Phenol | PPM | 4,430 | 5,315 |

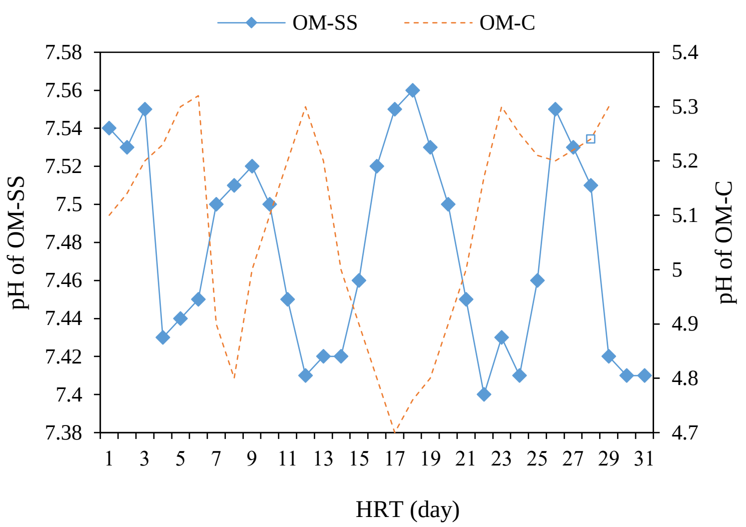


**Figure 2.** pH variation during digestion of substrate for OM-SS and -C

Many researchers have reported that the pH range of 5.0-6.5 is the optimum one for methane production from OM-C under an anaerobic process. In this regard, it was controlled by adding calcium bicarbonate to the substrate of OM-C (Khoufi et al., 2007; Blika et al., 2009; Goncalves et al., 2012; Boskou, 2012; El Hajjouji et al., 2013; Carlini et al., 2015; Ouazzane et al., 2017; Souilem et al., 2017; Nsair et al., 2020). During the digestion process, due to the decrease of COD and conversion of TN, the pH is subject to alternation. In this context, the pH value was maintained within the range of 4.8-5.3 during the digestion of the substrate for OM-C. Obviously, the pH reading data dropped to the lower limit synchronously with the HRTs during the first two weeks of the digestion process. The microbial growth is preferably feasible in a medium having this pH range for biogas production. This finding is attributed to the characteristics for the substrate of OM-C. The C/N ratio is in the range of 2.7-3.1, as indicated in Table 1. Hence, the ammonia product's concentration increases as higher TN content is obtained in the substrate. This would bring the pH values to slightly acidic ranges. The addition of calcium bi-carbonates raises the pH and obviously modifies the habitat for the microorganisms. Eventually, more gas production rates are foreseen.

### 3.3 Biogas pressure

The biogas pressure was used as an indicator of gas production in the batch reactor. The results of the biogas pressure from the digestion of the substrate of OM-SS and -C are represented in Figure 3. The pressure profile indicates that there are significant peaks in the pressure progress explicitly obtained at the end of the first two weeks of the digestion process. This is attributed due to the increasing methanogenic activity of the COD consumption and dewatering phase, resulting in the increase of carbon dioxide and hydrogen content (Khoufi et al., 2007; Athanasoulia et al., 2012). After the third week, the pressure progress is seen to have declining values, indicating that the methanogenic process is reaching the stabilization stage. The high production of gas from OM-C causes the continuous release of the produced gas to the gas holders, which affects the monitoring records of the gas pressure in such an experiment. It is noticed that the gas pressure of OM-C experiment has multiple peaks during the first two weeks. During the third week of the digestion process, the pressure progress reaches stabilization, and then the declining values are obtained due to the termination of the methanogenic process, thanks to the regular mixing of the substrate that provides sufficient homogeneity of the OM-C medium. Parallelly, the lower figures for the biogas pressure are obtained in the case of OM-SS experiments. This is attributed to the particularly lower COD, BOD, and TN contents of OM-SS, compared with the OM-C substrate (Table 1).

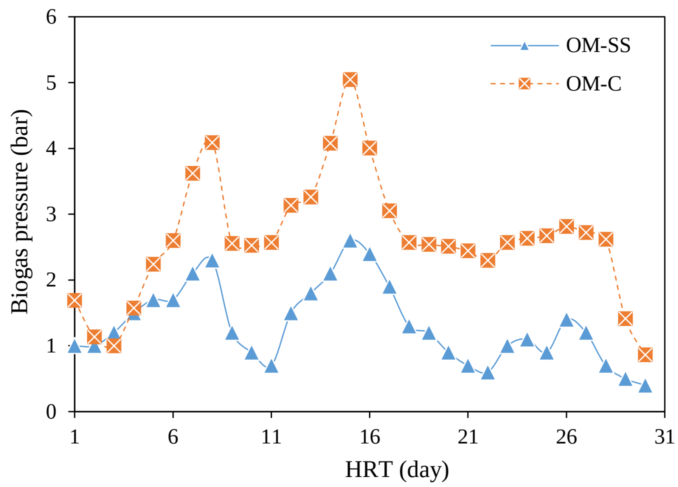


**Figure 3.** Biogas pressure from digestion of substrate for OM-SS and -C

### 3.4 Biogas productivity

The collected and accumulative biogas products from the digestion of the substrate for OM-SS are presented in Figure 4. As shown, two significant peaks in the collected biogas volume profile are obtained which are synchronous with the peaks of the biogas pressure progress in Figure 3. For the OM-SS substrate, the C/N ratio is in the range of 9-12 as indicated in Table 1. Hence, less nitrogen derivatives are accumulated in the form of an ammonia product, leading to maintain the pH reading of the substrate mainly in the neutral range. This lowers the habitat of microorganisms for COD biodegradation and eventually, the gas production is reduced.

As the pH reading is kept within an almost neutral range-the less disincentive media for the growth of the gas-producing microorganisms-less production rates are eventually achieved. An accumulative biogas volume of 210 L is obtained at the end of the digestion process of OM-SS. The average rate of the produced biogas exceeds the value of 7.0 ($L_{Biogas}$/day). In current investigations, the enhanced rates of biogas production are attributed to the regular mixing as well periodic pH mentoring acts, which provide the optimal conditions for the bio-degradation of COD, leading to promising biogas production rates.

The collected and accumulative biogas volumes from OM-C are depicted in Figure 5. As observed, three peaks in the collected biogas profile are obtained during the first, second and fourth weeks of the methanogenic process for the substrate of OM-C. An accumulative biogas volume of 936 L was obtained at the end of the digestion process of the substrate for OM-C. An average biogas production rate achieved the value of 31.2 ($L_{Biogas}$/d) for OM-C which is higher than the value obtained for OM-SS. In continuation to this, the higher recorded rates of biogas production in the current investigation could be attributed to the higher content of COD in OM-C with respect to OM-SS.

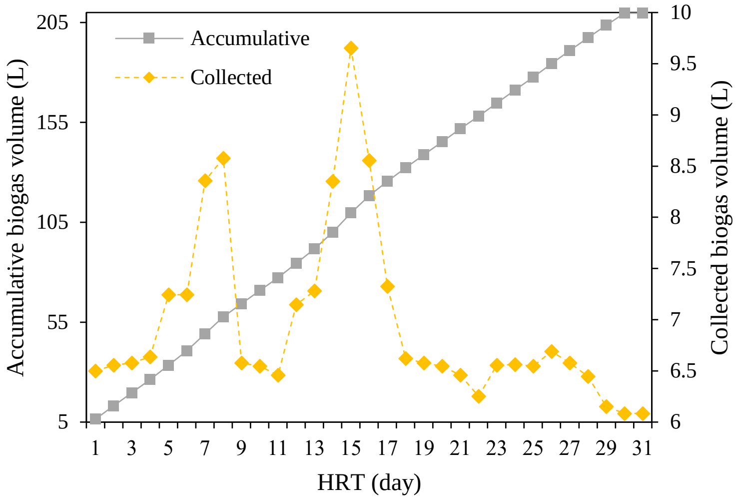


**Figure 4.** Accumulative and collected biogas volumes from the digestion of substrate for OM-SS

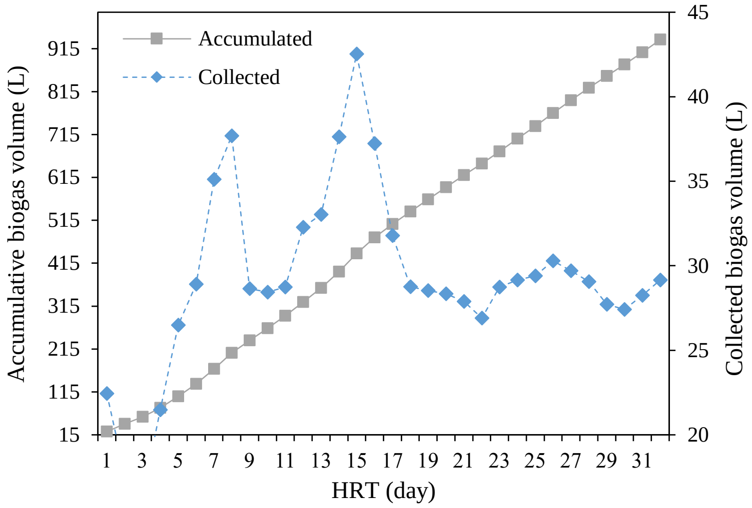


**Figure 5.** Collected and accumulative biogas volumes from digestion of substrate for OM-C

### 3.5 Substrate removal

The assessment of the biogas productivity could be elucidated by the conversion of the characteristic parameters in the stock substrates over the whole course of the digestion process. Figure 6 depicts the overall removal efficiency of the substrates for OM-SS and -C after the scheduled HRTs of 30 days and under the foreseen chrematistics of the feed mixtures. It was found that the substrate's removal efficiencies for the characteristic parameters in Table 1 are reported as following: for COD removal, it is about 46 and 52% for OM-SS and -C respectively. The BOD removal reaches close values of 40% for OM-SS and 43% for OM-C, TSS removal efficiency is 15% for OM-SS and 11% for OM-C, while 32% and 44% are attained as the TN consumption for OM-SS and -C, respectively. Neutralising the pH figures by the addition of calcium bi-carbonates had a positive effect on the bio-degradation of phenols. Obviously, the immobilization of the harmful phenol is reaching a promising percentage of 91% for OM-SS and 90% for OM-C which means that the remaining effluent phenol is below the perilous limits of the influents. Principally, the effluent substrates obtained from the digestion process could be considered eco-friendly for the environment. Besides their potential organic content, it would be suggested that these effluents are to be implemented in further ecological and economic perspectives; in agricultural applications such as soil amendments and fertilizer, livestock bedding, even in combustion after being desiccated in special molds (Niaounakis and Halvadakis, 2006; Gholamzadeh et al., 2016; Ouazzane et al., 2017; Souilem et al., 2017).

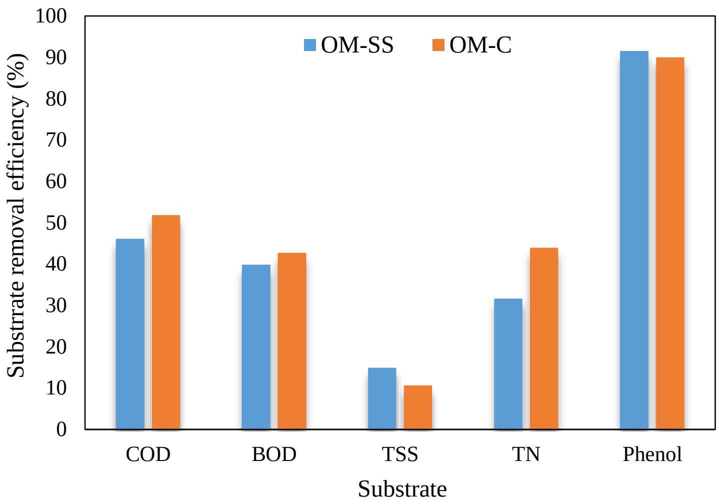


**Figure 6.** Substrate removal efficiency of substrates for OM-SS and -C

### 3.6 Biogas yield calculation

Based on the bio-degradation process, COD is eventually consumed during the microbial growth while $CH_4$, $CO_2$, and traces of other gases are produced. Due to pH fluctuations and the variation of the pressure progress inside the reactor, the production rate is dynamic and apparently relies on the dominant aerobic process during the primary HRT of the digestion process, whereas in delayed HRT it depends on the anaerobic process. This finding is confirmed by the variation of the biogas constitution with respect to $CH_4$ and $CO_2$ gases. In Figure 7, the $CH_4$ and $CO_2$ gas volume percentages are diagrammed for HRTs of 10, 20, and 30 days during the methanogenic process. COD consumption leads to co-generation of $CH_4$ and $CO_2$ and traces of other gases like $H_2$ and CO. During the first HRT period, the $CO_2$ yield is high with unpretentious $CH_4$ productivity. This is attributed to the dewatering/aerobic phase of the digestion process (Aquilanti et al., 2014; Bouknana et al., 2014). On the other hand, the biogas composition is getting reversed after the third HRT period of the digestion process. Hence, a reduction of COD content is performed mainly under anaerobic conditions achieving relatively better $CH_4$ and lower $CO_2$ yield, in other words, improved biogas purity is achieved. Obviously, a higher $CH_4$ yield for OM-C is recorded than that of the OM-SS feedstock for a HRT period of 30 days.

According to the current findings, the achieved biogas production rates from the digestion of the substrate for OM-SS and -C exceeds 0.07 and 0.31 ($L_{Biogas}/(L_{ferm}\cdot day)$) respectively as shown in Table 2. In terms of the volatile materials' removal, a COD removal is obtained as 46.1 and 51.8% for the substrates OM-SS and -C, respectively. Eventually, a promising methane yield is obtained under mesophilic conditions. The achieved methane yields, which were calculated with respect to the loaded COD, exceed the figures of 57 and 116 ($L_{CH4}/kg_{COD}$) for OM-SS and -C, respectively. These considerable findings would imply potential economic perspectives.

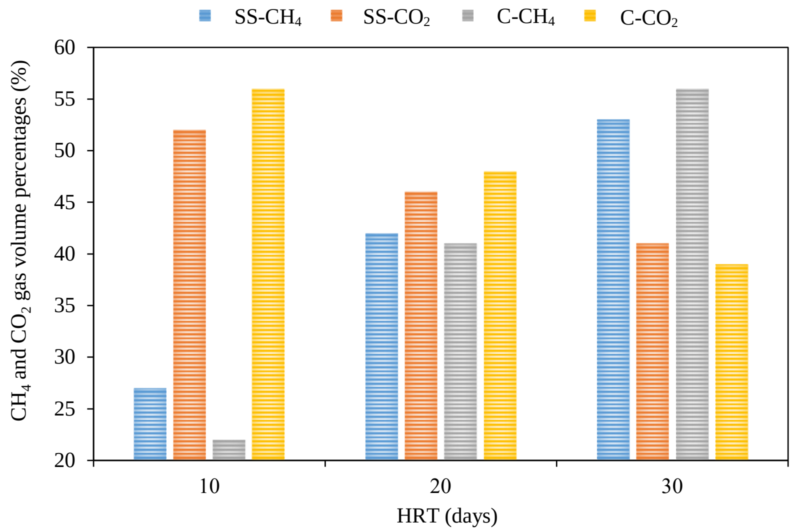


**Figure 7.** $CH_4$ and $CO_2$ gas content from digestion of substrate for OM-SS and -C, respectively

**Table 2.** Summary of biogas production rates and yields for substrates

| Parameter | Unit | OM-SS | OM-C |
|---|---|---|---|
| Average biogas production rate | ($L_{Biogas}$/d) | 6.99 | 31.20 |
| Average $CH_4$ production rate | ($L_{CH4}$/d) | 3.73 | 17.47 |
| Biogas yield | [$L_{Biogas}$/($L_{ferm}$.d)] | 0.07 | 0.31 |
| $CH_4$ yield | ($L_{CH4}$/$kg_{COD}$) | 56.84 | 115.80 |

For the determination of the gas quality of the produced biogas from the digestion of OM-SS and -C, an elemental analysis by gas chromatography of the gaseous products was performed as shown in Table 3. The analysis shows that higher methane and syngas contents were achieved from the digestion of OM-C (56.0 and 6.3% respectively), compared to those obtained for OM-SS (53.4 and 4.4%). Generally, these findings are consistent with those in the literature of Blika et al. (2009). It makes worthy to highlight that the relatively higher methane and syngas have acceptable heating values in the frame of the produced biogas' quality (Aquilanti et al., 2014; Souilem et al., 2017). More than this, the obtained biogas shows lean fractions with respect to the nitrogen content; eventually, $NO_x$ emissions are foreseen within acceptable limits from biogas combustion. Besides that, the produced biogas is considered to be eco-friendly with respect to other harmful emissions like $H_2S$, considering its minor content in the traces range.

The heating value of biogas of pure methane gas is 55,200 (kJ/kg) (Niaounakis and Halvadakis, 2006; Gholamzadeh et al., 2016; Ouazzane et al., 2017). Due to the significant carbon dioxide volume fraction, the heating value of the produced biogas with 54% methane by volume is estimated to be 17,100 (kJ/kg). In Jordan, around 120,000 $m^3$ of OM wastewater are produced annually (Al-Zboon, 2017; Al-Zboon, 2020). Based on current findings, around 20,000 $m^3$ of biogas is produced annually. Biogas is principally similar to natural gas with regards to the heating value after carbon dioxide is being removed. It could be easily combusted for other heating applications as well for steam generation plants in order to produce electricity.

**Table 3.** Elemental analysis of produced biogas from the anaerobic digestion of OM-SS and -C

| Gas compound | Formula | Gaseous content (%) | |
|---|---|---|---|
| | | OM-SS | OM-C |
| Methane | $CH_4$ | 53.4 | 56.0 |
| Carbon dioxide | $CO_2$ | 41.0 | 36.0 |
| Nitrogen | $N_2$ | 1.1 | 1.6 |
| Syngas | $CO+H_2$ | 4.4 | 6.3 |
| Oxygen | $O_2$ | 0.1 | 0.1 |
| Hydrogen sulfide | $H_2S$ | Traces | Traces |

### 3.7 Comparison with other studies

The current findings are found to be very meaningful with regards to their remarkable achievements, and upon being assessed with other relevant studies and their corresponding findings, they are summarized as shown in Table 4. According to Goncalves et al. (2012), the OM effluent was digested in a hybrid reactor to maximize the bioenergy recovery from OM. Compared to current investigations, a reported biogas production rate of 3.16 [$L_{Biogas}$/($L_{ferm}$·day)] was achieved at a continuous COD loading rate of 7.1 [$kg_{COD}$/($m^3$·day)]. A relatively short HRT of 7.5 days was implemented for an acidic substrate. Meanwhile, the unpretentious value for a maximum COD removal of 61% was stated. Their technique requires special arrangement for COD loading as well an OM pretreatment in order to remove coloration mainly caused by the remaining recalcitrant phenolic derivatives. Based on the investigations of Blika et al. (2009), physico-chemical and bio-treatment with fungi OM wastewater was carried out in a continuous bioreactor for various HRTs of 20 and 30 days, and 5.1 as a pH figure. Advanced figures of COD removal was 70 % and less methane gas of 0.4 [$L_{CH4}$/($L_{Ferm}$·day)] was attained under a loading rate of 1 $kg_{COD}$/[$L_{Ferm}$·day], their HRTs are close to current investigations. This is attributed to possible adsorption of long-chain phenolic compounds that are perilous to methanogens activities, and hence, lower the inhibition of the methanization process. In the work of Carlini et al. (2015), the anaerobic digestion of OM-C and cattle slurry in a batch reactor under mesophilic conditions and a neutral medium of pH equals 7.1. The Hamble biogas productivity was 0.73 [$L_{Biogas}$/($L_{ferm}$·day)] in spite of a relatively long HRT of 55 days. This can be attributed to a TS limitation of 14%.

**Table 4.** Summary of current results and those of relevant studies on the OM treatment

| Substrate | COD removal (%) | $CH_4$ yield | Process conditions | Reference |
|---|---|---|---|---|
| OM-SS | 46.1 | 56.84 ($L_{CH4}$/$kg_{COD}$) | Anaerobic treatment of sewage sludge HRT 30 days, pH 7.4-7.6, 35°C | Current Study |
| OM-C | 51.83 | 115.8 ($L_{CH4}$/$kg_{COD}$) | Anaerobic treatment of sewage sludge HRT 30 days, pH 4.7-5.3, 35°C | Current Study |
| OM | 51-61 | 3.16 [$L_{CH4}$/$L_{ferm}$·day)] | Anaerobic hybrid reactor with post-treatment to extract coloration, HRT 7.5 days and pH=4.7 | Goncalves et al. (2012) |
| OM | 70 | 0.4 [$L_{CH4}$/($L_{Ferm}$·day)] | Anaerobic digestion Physico-chemical and bio-treatment with fungi in continuous bioreactor HRT (20 and 30 days), pH=5.1 | Blika et al. (2009) |
| OM-C and cattle slurry | - | 0.73 [$L_{Biogas}$/($L_{ferm}$·day)] | Anaerobic digestion, Batch reactor with mesophilic conditions, pH=7.1, HR=55 days, TS=14% | Carlini et al. (2015) |
| OM | 90-92 | - | • Anaerobic treatment in sequencing batch reactor<br>• Different influent organic loadings, effluent membrane separation | Chiavola et al. (2014) |
| OM-SS and sewage | 70-85 | Est. 32-34 $m^3_{CH4}$/$m^3_{Ferm}$ and 0.8-1.2 [$kg_{COD}$/($m^3$·day)] | Combined treatment of an- and aerobic digestion, HRT≥3 months, pH=7.6 and 35°C, obstacles with color and turbidity | Boukchina et al. (2007) |
| OM and WAS | 64-72 | 0.6 ($L_{Biogas}$/$kg_{COD}$) | 2 CSTR run under mesophilic conditions, several HRTs, pH 7.12 and 4.8 for OM and WAS respectively | Athanasoulia et al. (2012) |
| OM and WAS | 52.6 | 0.33 ($L_{Biogas}$/$kg_{COD}$) | Electro-chemical pre-treatment in continuous reactor followed by anaerobic treatment, pH=6.5-7.2 HRT≥4 months | Khoufi et al. (2007) |
| OM and organic wastes | 48 | 0.69 [$L_{CH4}$/($kg_{VS}$·day)] | Anaerobic treatment HRT=4-7 | Scaglione et al. (2008) |

A combination of pre- and post-treatment membrane separation besides the anaerobic digestion process for the substrate of OM with different COD loadings was implemented, to investigate the efficiency of sequencing batch reactor, which was investigated in the study of Chiavola et al. (2014). Promising COD removal was reported in the range of 90-92%, whilst this approach is sensitive to the phenol derivatives' concentration within the domain of the current investigations. Another approach is performed by Boukchina et al. (2007) where the combined treatments of an- and aerobic digestion for the substrate of OM-SS and sewage were implemented. This approach was scheduled for an HRT longer than 3 months under neutral and mesophilic conditions. Despite the obstacles with color and turbidity, a COD removal was obtained in the range of 70-85%. Thus, a promising biogas productivity was reported in the range of 32-34 ($L_{CH4}/L_{Ferm}$) for the organic loading of 0.8-1.2 [$kg_{COD}/(m^3 \cdot day)$]. These figures are considered as over-estimations and apparently are unrealistic in the frame of loading CODs. In the relevant domain for the investigation of HRT, alternations were performed on the anaerobic co-digestion of the substrate of waste activated sludge (WAS) with agro-cultural OM wastewater in two-cascade continuous reactors (Athanasoulia et al., 2012). With HRT up to 20 days, moderate COD removal within 64-72% and relatively low 0.6 ($L_{Biogas}/kg_{COD}$) were observed. Their results could be explained due to the dilution effect by implementing the two-cascade continuous reactors due to continuous OM feeding. In the study of Khoufi et al. (2007), an electro-Fenton and chemical pretreatment were carried out in a continuous reactor followed by an anaerobic digestion stage of OM under neutral pH figures and relatively longer HRT than 4 months. COD removal was 52.6% of the organic loading rate of 10 [$kg_{COD}/(L_{Ferm} \cdot day)$] and an average methane yield of 0.33 ($L_{CH4}/kg_{COD}$) From an economics point of view, such techniques with long retention times and poor biogas production rates must be further promoted to be commercially adapted. On the other hand, anaerobic treatment tests were proposed by Scaglione et al. (2008) for a relatively shorter HRT within 4-7 days in a lab-scale batch reactor with various substrates of OM with low food/biomass ratio, such as thickened activated sludge, kitchen, fruit and vegetable wastes, and fresh grass. Lean COD removal was recorded with a value of 48% along with the poor biogas production rate of 0.69 [$L_{CH4}/(kg_{VS} \cdot day)$]. Obviously, this approach had stated a close $CH_4$/biogas quality with respect to the current findings, but it requires special processing of feedstock substrates to enhance the relevant outcomes of current investigations.

Based on these envisioned results, the biodegradation of OM with other diverse substrates and biomass, from beverage and food manufacturing facilities as well other agro-industrial wastes, merit further investigations in the batch as well continuous digestion operations. The visualization of such research portfolios in real operating facilities are highly recommended, as it which would have a great impact on the improvement of socio-economic relations/improving the infrastructure of rural areas and olive oil producing territorials.

## 4. CONCLUSION

Experimental investigations were conducted for the anaerobic digestion of the substrate mixtures of OM-SS and -C. The operating conditions for the anaerobic methanogenic digestion were relatively feasible; HRT of 30 days under a mesophilic temperature of 35°C. The pH readings were maintained within the neutral range for the anaerobic digestion of OM-SS, and slightly acidic for that of OM-C, through regularly adding defined amounts of calcium bi-carbonate to the reactor. By virtue of these envisioned results, the potential production rates of biogas with the promising methane quality was obtained from the anaerobic methanogenic digestion. Moreover, the digestion of OM-C was more productive with the factor of about two times than that of the OM-SS substrate, due to the considerable higher N/C ratio as well for the higher volatile organic content in the substrate of OM-C with respect to that of OM-SS. For the achievement of an optimal margin performance of digestion for the substrate of OM-SS and -C, the required chrematistics, as well other nutrients are essential for microorganisms' growth like nitrogen and Sulfur derivatives, must be ample, and specifically regulated.

The achieved OM methanogenic digestion is branded as a promising strategy to be adopted in olive oil producing territories, upon the assessment of the remarkable yielding of biogas production with a valuable methane quality. This industrial application would be helpful in enhancing the eco-friendly practices to cope with climate unpredictability due to their minimization of pollutions and greenhouse emissions which reduce the OM residues, providing technical solutions for energy demands in rural areas.

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