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Utilization of citrus, date, and jujube substrates for anaerobic digestion processes

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Abstract: This research explores the potential for generating biogas and clean energy by processing organic waste, a process that can become a sustainable solution to Syria's energy needs. Focusing on agricultural residues generated from citrus fruit orange, date, and jujube cultivation in Syria, this study evaluates the potential for anaerobic digestion of these residues for biogas production. It highlights the influence of substrate composition and the optimization of fermentation processes on biogas and methane production. The study focuses on evaluating the anaerobic digestion process by examining various dosages ranging from 20% to 50% dry matter for citrus orange waste, and different types of substrate with a fixed ratio of 20% substrate dry matter. It specifically discusses the factors influencing the inhibitory effect of anaerobic digestion, giving particular consideration to orange waste, a significant byproduct of the citrus industry. The biogas produced maintained a stable methane content when a citrus-to-inoculum ratio of 30:70 was used. Jujube waste, characterized by a composition rich in cellulose and hemicellulose, exhibited a higher potential for biogas and methane generation among the fruit waste investigated, particularly when combined with the inoculum in a 20:80 ratio. The research findings underscore the potential of using Syrian agricultural residues, including orange citrus peel, date, and jujube fruit, for the production of biogas through anaerobic digestion. © 2024 The Author(s). *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: anaerobic digestion; biogas; citrus; date; jujube

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Introduction

Syria, a semi-arid country, is noteworthy for its agriculture sector. However, this adds significantly to water scarcity problems stemming from the challenges of organic waste management.[1] The livestock sector, in particular, represents up to 35% of the value of agricultural production.[2] However, a significant amount of agricultural and food waste, including olive and citrus residues, remains unutilized; for example, in 2010, the average production of olive waste was 391 999 tons, whereas citrus residues amounted to approximately 111 799 tons.[3] It is essential to explore the untapped potential of organic waste processing to generate biogas and clean energy given the vital role of the agricultural sector in Syria, along with the possibility of using this waste as organic fertilizer. Syria's abundant organic waste provides an opportunity for the implementation of biogas production technology, thereby contributing to the region's sustainable rural development.[3]

Recent years have seen a significant increase in the generation of agro-waste due to the expansion of agriculture on a global scale. Citrus is one of the most popular, commonly grown, and commercially significant fruit species in Mediterranean countries. In 2021, the production of citrus fruits for the Syrian Arab Republic was 868 814 tons. It is an important crop in that country and is consumed both as fresh fruit and as citrus juice. It also plays an important role in the incomes of farmers and in the national economy. The most important commercial commodities include oranges, grapefruits, lemons, tangerines, and to a lesser extent, tangelos.[4] Syria ranked seventeenth globally in citrus production in 2009/2010, generating 1.093 million tons. Orange production reached 792 227 tons in 2013.[5]

In Europe, the annual amount of citrus waste generated in the processing of citrus fruit is about 12 million tons. One of the biotechnological approaches for exploiting orange-peel waste involves utilizing it for biogas production,[6] which can generate energy and other useful products. Syria faces a growing shortage of conventional energy resources, which is driving the development of strategies to address the growing energy needs of local communities. In this context, increasing the value of waste, including fruits such as citruses, dates, and jujube, not only helps reduce waste but also offers a viable pathway for the production of renewable energy, which is particularly crucial for developing countries due to high prices and limited access to conventional energy.[7]

The orange is the most widely cultivated fruit in the world and represents about 50% to 60% of the total citrus production. Syria is one of the main producers of citrus fruit in the Middle East, and a significant amount of citrus waste is likely generated as a result of the processing of these fruits. Similarly, jujube trees in Syria have traditionally been cultivated for their fruits. Although jujube cultivation and consumption have historical roots[8] in Syria, specific details and cultural practices may vary according to local traditions and preferences. The Indian jujube (*Ziziphus mauritiana*) is a native fruit tree in South Asia, including India, Pakistan, Bangladesh, and Sri Lanka. It is widely consumed in South America, Africa, and tropical and subtropical regions of Asia. Plants that are 1–2 m tall often yield less than five fruits in a season. In a single season, large plants (>5 m high) can yield 5000 or more fruits.

Date waste is another significant source of organic waste in Syria, as Syria is one of the world leaders in date cultivation. Culturally and economically valued in Syria, date palm thrives in arid regions such as Palmyra and the Euphrates Basin, and the Ministry of Agriculture has nurtured its growth since 1986.[9] The date palm ecological belt includes most Syrian desert land with a rainfall average of less than 200 mm per year. Palm cultivation is concentrated in the areas of Palmyra and Abu kamal. The cultivated area is 1900 ha, with 500 000 trees, and the annual production is 4300 tons.[10] According to the Food and Agriculture Organization Statistics (FAOSTAT Database) Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT), in 2019, Syria produced more than 175 000 tons of dates, representing more than 1% of the world's production. In Syria, dates are usually harvested from trees by hand, so a significant amount of date waste remains on site. This waste can be used to produce biogas, manure, and other products. However, the use of date waste in Syria is negligible, and most of the waste ends up in landfills and waste depots.

The production of biogas from citrus, dates, and jujube waste can be an effective way to reuse these wastes and reduce the negative impact on the environment. Anaerobic digestion technologies for the processing of organic waste to produce biogas and biofertilizer are widely known and utilized. They involve the degradation of organic materials by anaerobic bacteria in the absence of oxygen, resulting in the production of biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2). Anaerobic digestion also converts waste biomass into digestate, an organic fertilizer with agricultural benefits. Various parameters, including substrate composition and fermentation process optimization, influence the composition and activity of microbial consortiums, thus affecting biogas production.[11] The utilization of digestate as fertilizer reduces the dependence on chemical fertilizers, mitigating environmental impacts.[12] The biogas generated can also be used for heat or energy production, adding value to waste utilization.[13] However, when dealing with fruit substrates for anaerobic digestion there are initial challenges, such as rapid acidification of fruit wastes that inhibit methane production.[11] Fruit and vegetable fermentation is typically characterized by challenges related to low pH levels and suboptimal C/N ratios, which can inhibit methane production, and additional nitrogen sources may be required to stabilize the process and enhance biogas yield.[14]

Research[15] has highlighted that citrus wastes contain aromatic substances such as D-limonene, which are inhibitors of anaerobic digestion. Anaerobic digestion of citrus waste without prior extraction of limonene can prolong the time required to achieve methane production,[16] but certain pretreatment methods can introduce factors that affect biogas production negatively.[17]

Various approaches have been explored to improve the viability of anaerobic digestion of citrus waste. The co-digestion of manure with orange peel and algae offers a solution to inhibition problems, improving bioenergy outcomes, and promoting sustainable waste disposal.[18] Research has examined the biological production of hydrogen during anaerobic digestion of citrus wastewater, highlighting the potential for the production of hydrogen and alcohols, such as ethanol and butanol.[19] Another study has investigated two-stage anaerobic digestion as a promising technology for the use of citrus peel waste and the improvement of the yields of bioenergy products.[20] The study by Lukitawesa *et al.*[21] emphasizes the effect of recirculation on the production of biogas from citrus waste, addressing its inhibitory nature by adjusting pH levels and removing the D-limonene content through filtration. Successful anaerobic digestion in the context of citrus waste often depends on optimizing the C/N ratios and total solids content in specific raw materials, as observed in previous studies.[22]

Dates contain a large amount of sugar and starch, primary chemical components in date palm, consisting of carbohydrates such as glucose, fructose, and cellulose,[23] which can be used in anaerobic digestion to produce biogas and could help to provide access to clean energy and to reduce greenhouse gas emissions. The methane potential of different parts of the date palm biomass (specifically, pedicels, fibrilium, petiole, fruit bunch, spath, palm and a mixture of all biomass samples) was investigated by Chandrasekhar *et al.*[24] The study concluded that palm biomass demonstrates higher efficiency in methane formation than other biomass samples, particularly palm frond elements, which exhibit a rich lignocellulosic morphology. According to the study by Ben Khedher *et al.*,[25] thousands of tons of date palm waste, which has no economic value, can be recycled, thus contributing to energy conservation and preserving a sustainable environment.

Although citrus waste presents limitations due to inhibitory effects, the anaerobic digestion of dates and jujube has not been researched extensively, despite the significant generation of waste from these sources in Syria. The aim of this study was to explore the potential and feasibility of using citrus, date, and jujube waste for the production of biogas through anaerobic digestion in Syria. To achieve this, an anaerobic digestion investigation was carried out under mesophilic conditions to assess biogas production and the biochemical methane potential (BMP) of citrus, date, and jujube waste.

Materials and methods

Feedstock description

Inoculum

The digested sludge (inoculum) used to initiate fermentation was sourced from a large-scale biogas plant (BGP) in Mořina, Czechia. This BGP, which has an installed electric power capacity of 526 kW, operates in mesophilic mode, primarily using cattle manure with some agricultural byproducts, at a temperature of 41 °C. The effluent was transported in 20 L plastic containers, ensuring the temperature remained above freezing. To reacclimate the inoculum, it was stored anaerobically in an incubator at 41 °C for 5 days.

Substrates

For the anaerobic digestion process, three types of substrate were used: orange citrus peel, Syrian date fruit residues, and jujube date fruit residues. All substrates were cut mechanically using a grinder to reduce the size of the particles, optimizing the fermentation process.

The orange peels were collected meticulously from two distinct fractions, specifically the Washington navel orange and Valencia orange varieties. These citrus varieties are prominent in the Syrian Arab Republic, contributing significantly to its citrus production. The jujube (*Ziziphus mauritiana*) cultivated in Syria was part of the collected substrates. Syria has numerous centers for date-palm propagation such as Abu Kamal, Palmyra, Sabkha Al-Moah, Al-Rigga, Al-Khobar, Balash in Al-Hasakah, and the Badia Damascus countryside. The varieties of Syrian dates include Zahdi, Ashrasi, Khastawi, Al Maktoum, Al Burahi, Barben, and Dijla Nour.[10]

Setup for batch experiment

Wet anaerobic co-digestion was investigated under mesophilic conditions to examine biogas production and the biochemical methane potential (BMP) of citrus, date, and jujube waste.

Research was carried out using 12 single-stage laboratory-scale reactors (1500 mL plastic vessels) placed in a water thermostat reservoir. The characteristics of substrate loading ratios are given in Tables 1 and 2. Each batch had three replications, was tightly sealed, and all reactors operated simultaneously at 41 °C. Nitrogen was used to purge the batches, effectively removing the air. During the experiment, biogas production was measured daily over the 45-day incubation period using the downward displacement method, which relies on water displacement, and the pH inside the digesters was not controlled. Transparent glass jars with a capacity of 3 L were used to collect the biogas and were placed in a distilled water basin (Fig. 1). As biogas bubbles passed through the water layer they displaced the water level in the jars.

Analytical methods

The characteristics of the inoculum were quantified using standard methods for the examination of water and wastewater.[26] Total solids (TS) were analyzed by filtering a well-mixed sample through a standard weighed glass-fiber filter, with the residue retained in the filter dried to a constant weight at 104 °C for 40 min. The residue from this method was then ignited to a constant weight at 550 °C for 30 min, with the weight lost on ignition representing the total volatile solids (TVS). The characteristics of dry and organic dry matter in the substrate were quantified according to the Association of German Engineers standard VDI 4630, involving drying at 105 °C to a constant mass, followed by incineration at 550 °C after prior drying to a constant mass. The characteristics of the influent substrates are shown in Table 3. The pH parameters were measured using a Professional Laboratory Multimeter HANNA (Woonsocket, RI, USA). The composition of organic matter, nutrient content, and moisture levels varied between substrates, influencing their respective biodegradability and biogas production potential.

The methane and carbon dioxide content of the biogas was analyzed using the Aseko gas analyzer AIR LF (Prague, Czech Republic), which employs linear nondispersive infrared (NDIR) sensor technology to measure the biogas composition. This method, based on infrared radiation absorption, is highly reliable and provides stable data. The AIR LF gas analyzer can determine a spectrum of gases, including CH_4, CO_2, O_2, H_2S, H_2, and NH_3. The gas flow during the analysis is controlled between 0.5 and 0.7 $L{\cdot}min^{-1}$, with measurement repetability quantified at 2% to 3% of the full scale.

Results and discussion

Anaerobic digestion of citrus waste

To assess the fermentation process of citrus residues, citrus material dosages for fermentation ranging from 20% to 50% of dry matter were tested, as indicated in Table 1. The orange peel substrate has an acidic environment, as evidenced by the recorded pH values presented in the Table 3. Starting the loading stage with the citrus substrate leads to a decrease in the pH value at the initial stages, which affects the activity of methanogens.[27]

The biogas production results are shown in Table 4. Anaerobic digestion under mesophilic conditions reveals a significant inhibitory effect attributed to the citrus content. This effect is notable through the 50:50 citrus-to-inoculum batch ratio, where the inhibitory influence is particularly pronounced. For the 50:50 citrus to inoculum test batch, a minimum biogas production of 87.54 $L/{\cdot}kg^{-1}$ dry matter was obtained, with a significant reduction in the total anaerobic digestion period to 15 days, in comparison with a 38-day digestion process for other ratios. Other variations of the ratios are shown in Fig. 2. This illustrates the dynamics of biogas production during the anaerobic digestion period. In Fig. 2, the progression of methane production is presented throughout the anaerobic digestion period, comparing the ratios of 20%, 30%, and 40% citrus to inoculum. Based on the citrus content in the substrate, the highest amount of biogas was obtained when citrus was added at a 20% citrus 80% inoculum ratio. The total biogas production amounted

Table 1. Batch tests parameters with different ratio.

Batch material	Fresh matter weight of input inoculum per 1 kg of mix (g)	Fresh matter weight of input citrus per 1 kg of mix (g)	Dry matter ratio substrate:inoculum (%)	Dry matter (TS) of mix batch material (%, FM basis)	Organic dry (*VS*) matter of mix (%, TS basis)
Inoculum	1000	0	100	7.71	81.17
Citrus: inoculum	830.67	67.09	80:20	7.99	84.15
	728.14	100.76	70:30	8.00	85.65
	624.16	134.23	60:40	8.00	87.14
	519.76	167.98	50:50	8.00	88.64

Abbreviations: FM, fresh matter; TS, total solids; *VS*, volatile solids.

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Table 2. Batch tests parameters with different substrate.

Batch material	FM weight of input inoculum per 1 kg of mix (g)	FM weight of input citrus per 1 kg of mix (g)	Dry matter ratio substrate:inoculum (%)	Dry matter (TS) of mix batch material (%, FM basis)	Organic dry (*VS*) matter of mix (%, TS basis)
Inoculum	1000	0	100	7.71	81.17
Dates: Inoculum	837.91	17.86	80:20	8.06	84.49
Jujube: Inoculum	807.02	87.72	80:20	7.77	84.34
Citrus: Inoculum	624.16	134.23	80:20	8.00	84.15

Abbreviations: FM, fresh matter; TS, total solids; *VS*, volatile solids.

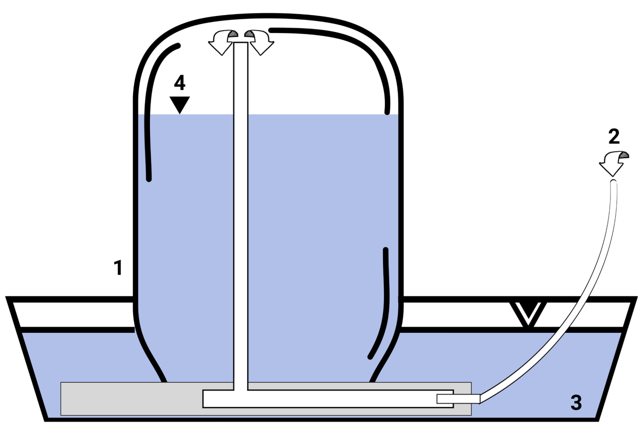

Figure 1. Equipment for measuring biogas volume based on water-column measuring system: 1 glass jar; 2 biogas input; 3 water basin; 4 biogas produced.

Table 3. Characteristics of influent substrates.

Material	pH	Dry matter (TS) (%)	Organic dry matter (*VS*) (%)
Inoculum from biogas plant	7.88	7.70	81.17
Citrus	5.56	23.80	96.11
Jujube	5.30	17.70	97.03
Dates	5.60	90.30	97.77

to 36.2 L. The peak biogas production at this ratio occurred on days 19–21 after the initiation of the anaerobic process. On the other hand, with an increase in the citrus content on the substrate (30:70 and 40:60 citrus-to-inoculum ratios), the amount of biogas generated decreased to 26.9 and 22.52 L, respectively. A substrate consisting entirely of 100% inoculum showed intermediate results, with a total biogas production of 26.55 L, and the maximum biogas production also occurred on days 21–23.

Figure 2 shows that a higher dose of citrus material corresponds to a decrease in biogas production. The citrus to inoculum ratios of 20:80, 30:70, and 40:60 exhibit similar behavior in the initial stages. In particular, the curve demonstrates an initial deceleration in biogas production during the early phases. In the first days of biogas generation, the presence of readily available soluble sugars (glucose, fructose) promote the utilization of these easily accessible substrates by methanogens for biogas formation. However, a contrast is observed regarding the control scenario, suggesting that the presence of limonene in the initial stages retards this process.

In the 30:70 citrus to inoculum batch and the control inoculum the total volume of biogas produced and the dynamics of methane yield had similar profiles (Fig. 3). The observed differences in substrate transformation rates can theoretically be explained by the slower decomposition of hemicellulose and cellulose, two other major citrus compounds, resulting in higher biogas production compared to the control in the period from day 28 to day 34. Methane formation was more stable, which is possibly related to inhibition resulting from the presence of limonene.[28]

However, a lower dose of 20:80 citrus to inoculum showed a higher level of methane formation for the first 10 days, but then a gradual reduction in methane generation was observed due to the depletion of the easily available substrate during the active methane formation period.

The addition of citrus at a 30% level of the dry matter of the inoculum can show the stability of the methanogenesis process but with a 10%–15% inhibition effect in total. The addition of 40% citrus in the initial 10 days was accompanied by methane content profiles similar to the 30% citrus batch, but a possible accumulation of limonene after material decomposition resulted in a slight decrease in methane production on day 12. Meanwhile, the addition of 20% citrus content, potentially combined with substrates that can provide an available substrate for methanogenesis after the tenth day of biogas production, has the potential to be used in combination with other organic substrates. It shows a minimal effect of inhibition of methane formation during the first 10 days. One study[29] demonstrated that the synergy between biowaste and the citrus substrate, influenced not only the biodegradation rates but also the methane production yields. Calabrò et al.[29] reported the following methane yield values: 395.6 Ln CH_4·kgVS^{-1} for a 50% blend of orange peel waste and biowaste, 359.5 Ln CH_4·kgVS^{-1} for orange peel waste alone, and 408.5 Ln CH_4·kgVS^{-1} for biowaste alone.

This research used citrus waste without prior extraction of limonene. This approach resulted in overall system productivity ranging from 148.9 to 202.6 L·kgVS^{-1}, depending on the citrus content, which varied from 20% to 40% of the citrus added to the inoculum. These results demonstrate the potential of citrus waste as a substrate for biogas production. To contextualize these findings, previous research has reported the biogas potential of untreated citrus waste with methane yield values ranging from 0.061 to 0.131 Nm^3 CH_4·kgVS^{-1} from chopped and homogenized peels with limonene.[17] An earlier study by Ruiz and Flotats[30] reported that the BMP values of the tested citrus waste, including orange peel, mandarin peel, mandarin pulp, and rotten fruit, ranged from 354 to 398 L CH_4·kgVS^{-1}.

Negro *et al.*[18] reported that the inhibitory levels of limonene fell within the range of 0.45% and 0.9% (w/w). The potential limonene content remained within inhibitory concentrations, exceeding 200 mg kg^{-1}, according to Ruiz and Flotats.[30]

However, Wikandari *et al.*[17] have demonstrated significant improvements in methane yield when limonene extraction was performed as part of the waste-preparation process. In these cases, the methane yield values reached 0.177 Nm^3·kgVS^{-1}, corresponding to a remarkable improvement, which ranged from 25% to 350%.[17]

However, it is important to acknowledge certain limitations associated with the extraction of limonene, notably the

Table 4. Biogas production performance of batches with different ratio of citrus.

Batch material	Biogas production (L·kgVS^{-1})	Methane production (L·kgVS^{-1})
Citrus 20: Inoculum 80	540.1	148.9
Citrus 30: Inoculum 70	390.3	202.6
Citrus 40: Inoculum 60	323.2	163.0
Citrus 50: Inoculum 50:	87.4	4.6
Inoculum 100	424.3	238.6

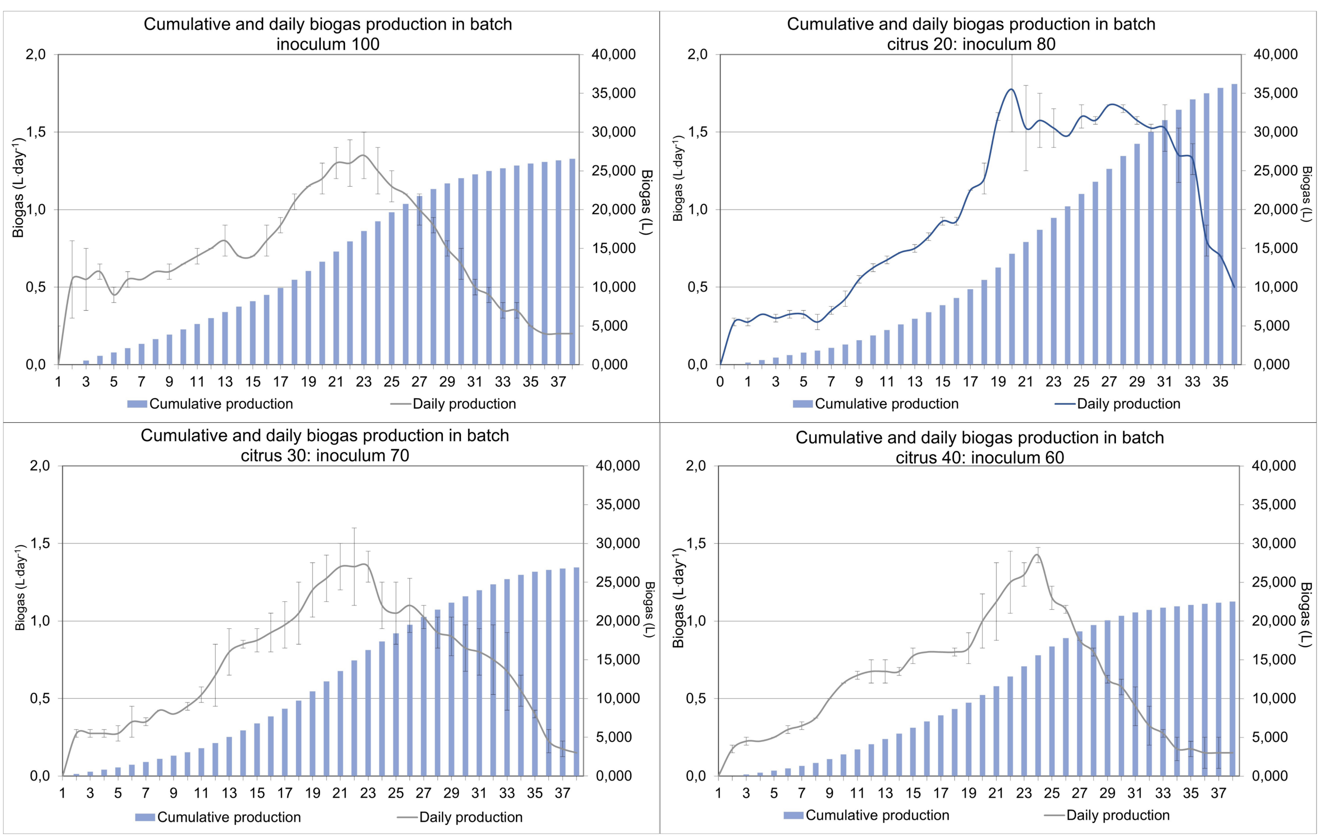

Figure 2. Biogas production performance with different citrus ratios.

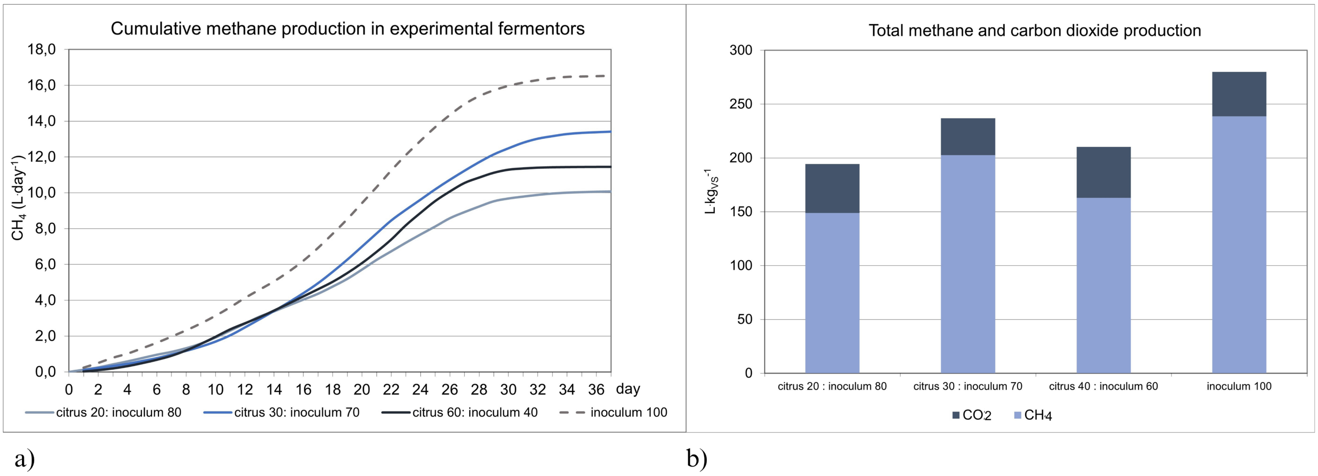

Figure 3. Methane production performance with different ratios of citruses (a) cumulative production; (b) total methane and carbon dioxide production.

challenges of selecting solvents that do not introduce inhibitory effects on the digestion process.[17]

According to Shao *et al.*,[28] generation of larger amounts of volatile fatty acids (VFAs) was observed in the presence of citrus waste in anaerobic digestion processes, promoting the stages of solubilization and hydrolysis, while simultaneously inhibiting the methanogenesis stage. A structural shift was therefore observed in the microbial community favoring the proliferation of fermentative microbes that produce VFAs. As the citrus dose increased, the composition of the VFAs showed an increase in acetic and butyric acids, replacing increases in propionic acid.[28] However, the adaptation of microorganisms to the limonene inhibition mechanism was observed over a longer time because recovery in biogas production was observed after initial inhibition.[30]

Our research has investigated the potential of citrus waste as a value-added substrate for biogas production, capable of providing system performance at a certain citrus content. Citrus waste is therefore a resource that can be used for biogas production in Syria, contributing to solving the problems of citrus waste disposal by reducing the amount of waste that goes to landfills.

Anaerobic digestion of Syrian fruit wastes

Anaerobic digestion was conducted to explore the potential for integrating common agricultural wastes from Syria – citrus, date and jujube – which would open up opportunities for sustainable waste management and renewable energy production. Upon evaluating various substrates, a composition ratio of 20% substrate to 80% inoculum, was used to obtain results in terms of biogas and methane production. The biogas and methane potential are outlined in Table 5 and Fig. 4.

Table 5. Biogas production performance with different substrates.

Batch material	Biogas production (L·kgVS^{-1})	Methane production (L·kgVS^{-1})
Jujube 20: Inoculum 80	633.2	178.7
Citrus 20: Inoculum 80	540.1	148.9
Date 20: Inoculum 80	407.2	117.2
Inoculum 100	424.3	238.6

Anaerobic digestion with a substrate ratio of 20% jujube and 80% inoculum yielded the highest biogas production at 633.2 L·kgVS^{-1}, characterized by a methane production of 178.7 L·kgVS^{-1}. However, anaerobic digestion with a substrate ratio of 20% citrus and 80% inoculum resulted in slightly lower biogas production of 540.1 L·kgVS^{-1} and methane production of 148.9 L·kgVS^{-1}. A substrate ratio of 20% date and 80% inoculum led to a decrease in biogas production of 407.2 L·kgVS^{-1}, along with a methane production of 117.2 L·kgVS^{-1}. These results emphasize the significant impact of substrate composition on both biogas and methane yields and contribute findings to the understanding of anaerobic fermentation of jujube and dates, where there is limited data. All substrates contain complex carbohydrates, including sugars and fiber, which can be degraded by microbial consortia to generate methane and other byproducts.[31-33] Jujube and date substrates have

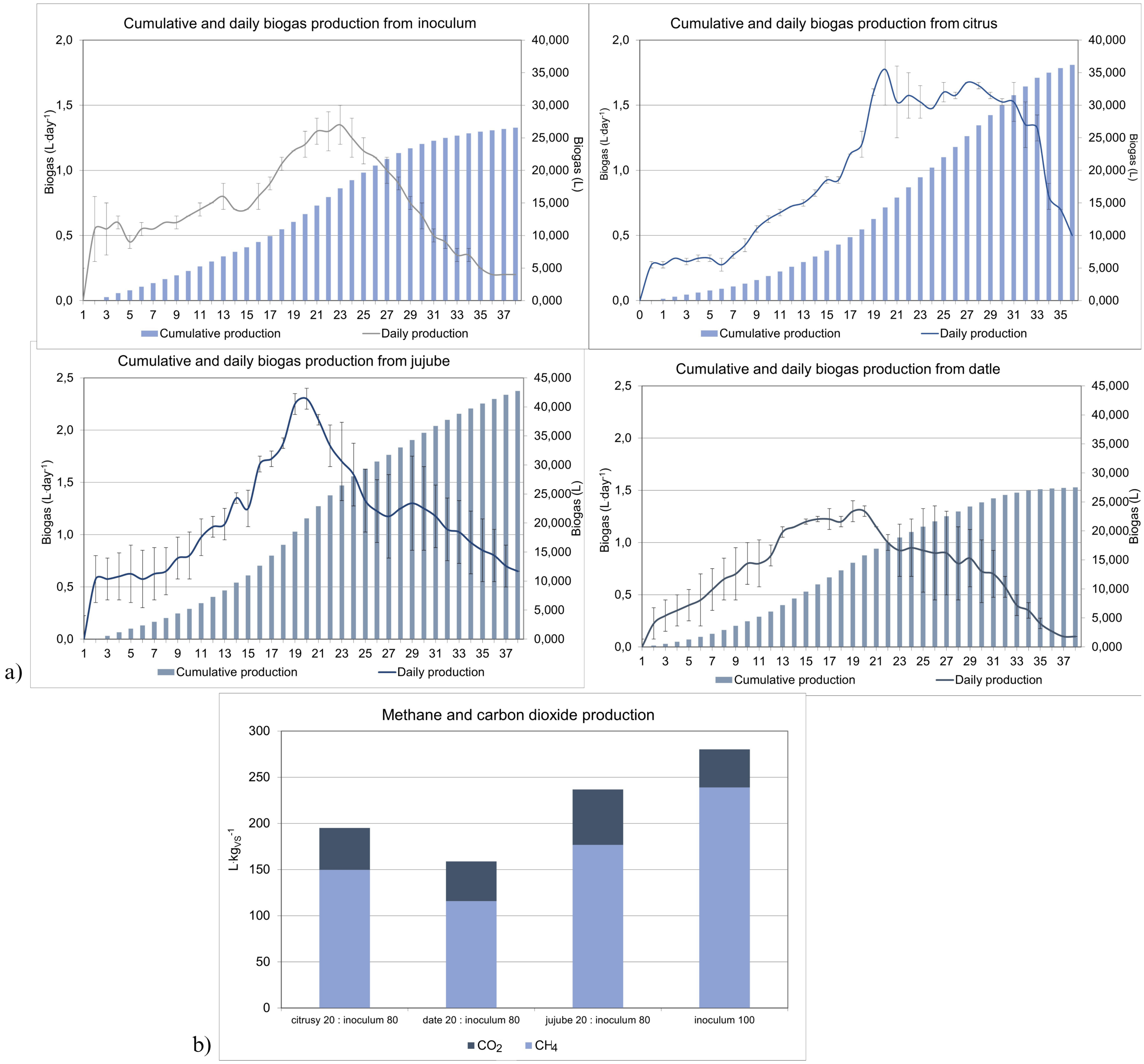

Figure 4. Biogas production performance with citrus, dates, and jujube substrate: (a) cumulative and daily production; (b) total methane carbon dioxide production.

lignocellulosic components, similar to citrus peels, which can be broken down into simpler compounds that contribute to methane production. The composition and characteristics of each substrate are important for maximizing and optimizing methane production.[34-36]

The composition of date waste is characterized by the prominent presence of a solid, insoluble part consisting mainly of cellulose, hemicelluloses, lignin, and insoluble proteins. This composition has a strong influence on the anaerobic digestion process, starting from the initial stage of hydrolysis. The resistance of lignocellulosic materials to anaerobic digestion requires careful preparation to enhance their biodegradability. Palm waste biomass, with significant hemicellulose, cellulose, and lignin content, presents challenges due to lignin hindering the decomposition of cellulose and crosslinking. Effective pretreatment methods, chemical, physical, or biological, become imperative for transforming the lignocellulosic structure, increasing enzymatic action, and improving hydrolysis to improve digestibility and biogas production in anaerobic digestion processes.[37] Studies by Ismail and Talib[38] have demonstrated increased biogas and methane yields due to additional

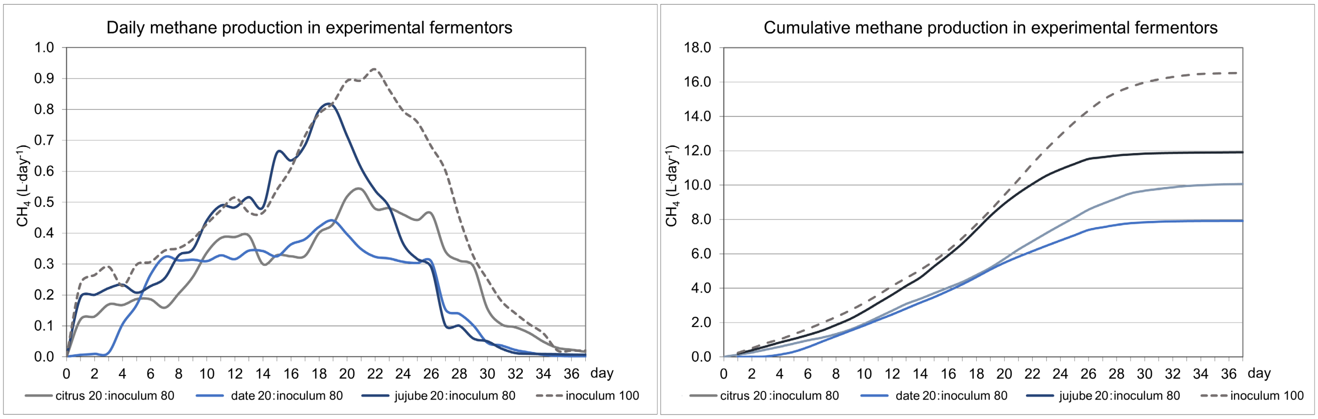

Figure 5. Methane production with citrus, dates, and jujube substrate.

chemical treatment, reaching 141.66 $L \cdot kgVS^{-1}$ and 90.38 $L \cdot kgVS^{-1}$, respectively. With alkaline and oxidative pretreatments, the methane yields increased from 130.71 L $CH_4 \cdot kg\ TS^{-1}$ to 211.55 L $CH_4 \cdot kg\ TS^{-1}$.[39] Alkali-NaOH pretreatment can improve biodegradability by up to 50%.[40] Removal of fibers from date palm fruit also leads to a better anaerobic digestion process,[32] and there is potential to combine date substrate with other nutrient substrates to improve fermentation performance.[41] Thermal and ultrasonic pretreatments also demonstrate an improvement in methane generation from palm waste.[40] The most significant increase in methane formation was observed with thermal pretreatment, accompanied by a reduction in the duration of the lag phase, which accelerated the digestion process.

In the context of the dietary fiber composition of the substrate, the fruits of jujube are characterized by the fact that cellulose is the most important fiber contained in the fruit, followed by hemicellulose and lignin,[42] but the jujube substrate is characterized by a high phenolic compound content (tannins and flavonoids).[43] At the same time, the bioactive ingredients and antioxidant properties of jujube fruit are not an obvious element of the substrate composition.[44] However, the composition characteristics of the substrate from jujube waste have not been investigated in terms of availability for methanogenic fermentation.

The results of anaerobic digestion shown in Fig. 5 demonstrate a higher biogas yield in general from the jujube substrate. Date fruit and orange peel primarily consist of pectic compounds,[45,46] whereas jujube polysaccharides are more abundant in monosaccharides.[47] However, in comparison with the inoculum, it is possible that the methanogenesis process could be restrained by the presence of phenolic compounds in jujube or the presence of limonene in the citrus substrate.

According to Rashwan *et al.*[48] jujube biomass can be an inexpensive byproduct resource with high yields, enhancing its commercial potential for use in anaerobic digestion processes. A study of different ecotypes of jujube revealed that fructose and glucose are the dominant components of the sugars present in the fruits.[49] Jujube has also been explored as a basis for activated carbon, with modifications that has the potential to improve its adsorption and separation capacity.[50,51] The potential application of jujube in the anaerobic digestion process was demonstrated in Fig. 4(b) as an approach to fruit waste management for energy production.

However, the co-digestion of fruit wastes, such as citrus, dates, and jujube, with other types of waste could potentially lead to successful anaerobic digestion. This approach can increase buffer capacity, balance nutrients, stimulate microbial synergism, and dilute toxic compounds, thereby improving the anaerobic digestion of available biomass wastes.[52]

Conclusions

This study has shed light on the potential of using agricultural waste from Syria – particularly citrus, date, and jujube waste – for the production of biogas through anaerobic digestion. These agricultural residues represent significant sources of organic waste and their efficient utilization can address challenges in waste management, reduce greenhouse gas emissions, and contribute to the production of renewable energy.

The findings indicate that, despite containing inhibitory compounds such as limonene, citrus waste can be a suitable substrate for biogas production under mesophilic conditions. The study explored various citrus to inoculum ratios, from 20% to 50% orange peel, and demonstrated that a 30:70 citrus to inoculum ratio exhibited stability in the methanogenesis process with a moderate inhibitory effect, resulting in a 15% reduction in methane production.

The study explored the anaerobic digestion of Syrian fruit waste, including citrus, dates, and jujube. It highlighted the importance of substrate composition, with jujube waste showing a higher potential for biogas and methane production than other fruit wastes when blended with inoculum in a 20:80 ratio, with a methane production of 178.7 $L{\cdot}kgVS^{-1}$. However, it also noted a moderate inhibitory effect, leading to a 25% reduction in methane production in comparison with the inoculum. Dates and citrus orange peel are also viable for anaerobic digestion but their methane production is comparatively lower than jujube waste when processed at the same substrate-to-inoculum ratio, with methane production of 117.2 $L{\cdot}kgVS^{-1}$ and 148.9 $L{\cdot}kgVS^{-1}$ respectively. These results highlight the varied potential of different agricultural wastes for biogas production and emphasize the importance of optimizing anaerobic digestion processes for sustainable waste management and renewable energy production from Syrian fruit waste.

Further research and optimization of anaerobic digestion processes with these agricultural residues can help unlock their full potential for biogas production and waste reduction.

Author contributions

Viktoriia Chubur: formal analysis, writing – original draft, writing –review and editing, data curation, statistical analysis. Ghaith Hasan: data collection, writing – review and editing. Jaroslav Kára: investigation, resources, data curation, writing – review and editing. Irena Hanzlíková: investigation, resources, data curation, writing – review and editing. Yelizaveta Chernysh: validation, writing – review and editing. Jan Sedláček: writing – review and editing. Jian Wang: writing – review and editing. Hynek Roubík: conceptualization, methodology, resources, supervision, funding acquisition, writing – review and editing.

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Conflict of interests

The authors declare that they have no competing interests.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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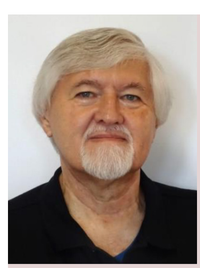

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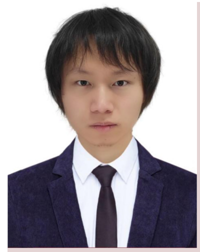

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