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Testing the ability of water hyacinth for wastewater treatment and methane biogas production

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ABSTRACT

This study aims to assess the potential of water hyacinth (WH) in treating wastewater and its viability for co-digestion with municipal solid waste to achieve zero waste treatment by generating methane biogas. A batch flow reactor treated wastewater, evaluating nine parameters (NO3, PO4, BOD5, Turbidity, Chromium, Cadmium, Lead, Calcium, and Magnesium). The highest removal efficiencies were observed for NO_3 (94.13%), PO_4 (75.85%), BOD_5 (100%), Turbidity (93.86%), Chromium (94.3%), Cadmium (94.93%), Lead (91.33%), Calcium (41.42%), and Magnesium (43.13%). The pH ranged from 7.82 to 7.44. Methane biogas production was examined using anaerobic digesters with varying ratios of carbon-based waste and WH, along with pH, temperature, and total solid content variations. The optimal methane biogas production ratio was found to be 1:3 for WH and solid waste at 35°C, 10% total solids, and a pH of 7.5, resulting in the highest cumulative methane generation of 1039.80 mL/gm vs. The Gompertz model accurately described methane biogas generation with a yield of 1083.088 mL/gm vs., supported by a coefficient of determination (R^2) of 0.999. The kinetics of the biodegradation process were evaluated using a first-order kinetic model. The negative value of k (-0.2364) suggests a rapid solid waste biodegradation, with a high correlation coefficient (R^2) of 0.9971. Numerous correlations were employed to enhance the production of methane, yielding a correlation coefficient of 91.36%.

1. Introduction

The recent rise in production and disposal of wastewater has led to a rapid increase in the eutrophication of the bodies of water that receive it. Conventional wastewater treatment methods, such as the activated sludge process, trickling filters, and rotating biological contactors, are often regarded as insufficiently efficient and energy-intensive [1-2]. Furthermore, the expenses associated with maintenance and operation are comparatively elevated. Recently, there has been a significant focus on utilizing aquatic plants in natural or man-made wetlands (such as aquatic treatment systems) to treat public and industrial wastewater [3-4]. This approach is particularly suitable for small settlements with ample open

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space and warm climates. The system is uncomplicated and does not necessitate advanced or bulky machinery, costly operations, or lengthy upkeep. Conversely, the production and elimination of substantial amounts of carbon-based waste without proper processing led to substantial environmental contamination and public health risks, resulting in the spread of illnesses such as malaria, cholera, and typhoid. Given the expanding populations and dwindling land resources for disposal, the management of this significant volume of rubbish is an urgent economic and environmental challenge. Soil, groundwater, and surface water contamination via leachate or direct contact with garbage are just a few examples of the serious environmental hazards that can arise from incorrect waste disposal. Without proper controls, emissions of greenhouse gases from waste incineration or anaerobic degradation can also contribute to air pollution. Not only that, but it can aid in disease transmission by insects and birds [5]. In contrast to other renewable energy sources, biogas can collect carbon-based waste, process it, and use the byproducts as fertilizer and water for irrigation purposes all at the same time. There are no technological or geographical barriers to the widespread use of biogas as an energy source. On top of that, it is easy to use and put into practice. One way to tackle the depletion of fossil fuel stocks, reduce emissions of carbon dioxide, and lessen the impact of climate change is to use biomass or carbon-based leftovers that have been sustainably produced instead of fossil fuels [6].

This study sets out to provide a solution to the problem of solid waste management by looking into a way to treat aquatic plants that also treat public wastewater and generate electricity for the treatment plant. The present study treated municipal wastewater using water hyacinth, scientifically known as Eichhornia crassipes (Mart.) Solms. The nitrogen and phosphorus used in the water hyacinth biomass were subsequently mixed with solid waste to produce methane biogas. One member of the Pontederiaceae family of monocotyledonous aquatic plants is the water hyacinth. Its extensive distribution encompasses a variety of tropical and subtropical zones, from the Nile River to southern America, Iraq, Pakistan, India, and the Philippines [7]. The development rate of water hyacinth is influenced by the presence of nutrients such as nitrogen and phosphorus, as well as temperature and the density of surrounding plants. The temperature range for plant growth typically falls between (18-33) ºC, with the most favorable growth rates observed between (22-33) ºC. Water hyacinth growth rates under high population density conditions are around (180-220) kg/ha.day based on dry weight [8].

2. Materials and Method

2.1. Wastewater treatment experiments

The water hyacinth (WH) was gathered from the Al-Meshkhab canal, which is situated in the Holly Najaf government, approximately 161 kilometers away from Baghdad (N: 31º 49’ 39.7’’, E: 044º 30’ 37.3’’). The gathered plant was placed in a plastic receptacle filled with water from the identical origin. The container was transported to the laboratory for research wastewater treatment. The plant underwent multiple rinses with tap water to eliminate the presence of suspended solids and biological organisms. The WH was placed in a glass tank to serve as a storage facility for subsequent tests. Wastewater samples were obtained from the influent of the Al-Qadisiyah wastewater treatment plant. The Al-Qadisiyah wastewater treatment facility is located in the Al-Diwaniyah Government, approximately 180 kilometers from Baghdad (latitude: 31º 57’ 4.58’’, longitude: 044º 58’ 17.89’’). The wastewater properties are displayed in Table 1. The wastewater treatment experiments were carried out using a glass tank measuring (100) cm in length, (40) cm in width, and (50) cm in height. The WH was obtained from the storage facility. The glass tank was filled with (100) liters of collected effluent. The water heater was deliberately placed within the tank. An electrical heater was used to maintain the temperature at (25±2) ºC. Initially, a pre-treatment sample of wastewater was collected to obtain pollutant concentration. Wastewater samples were collected periodically to quantify the decrease in influent concentrations. The clearance efficiency for each contaminant was determined using the following correlation:

$$Removal\ Efficiency\ \% = \frac{c_i - c_j}{c_i} \times 100 \tag{1}$$

Where:
C_i : Initial concentration and C_j: Concentration at any time.

A graph was created to illustrate the correlation between the initial concentration, removal efficiency, and detention time. Figure 1 displays a schematic depiction of the experimental apparatus. Figure 2 displays the treatment system.

2.2. Solid waste experiments

The solid wastes utilized in the current investigation were obtained from three transfer stations situated in the Al-Diwaniyah administration, specifically Al-Jazaer, Al-Sadr, and Um-Alkhail. The biodegradable carbon-based components (OFMSW) consisting of food waste, paper and boards, wood, and textile, account for around (77%). The remaining portion consists of the carbon-based fraction, which accounts for around (23%). In this study, the non-carbon-based component is excluded, and only the carbon-based fraction is considered. In order to transform the solid material into a slurry, the organic fraction of municipal solid waste (OFMSW) is ground into smaller pieces with a mechanical blender until they reach a diameter of less than (0.005) m. The purpose of this step is to ensure optimal functioning by preventing the obstruction of the digester. This phenomenon arises from the presence of dense organic waste that fails to reach the bacteria responsible for its digestion. The pH, moisture content (MC), density, total solids (TS), and volatile solids (VS) of OFMSW were tested and recorded in Table 2. Prior to the commencement of anaerobic digestion, a thorough mixing of all the raw ingredients is conducted.

Table 1. Characteristics of public wastewater

Constituent	Value	Unit
Temperature	20.100	ºC
pH	07.820	unit
Turbidity	36.500	NTU
Biological Oxygen Demand (BOD5)	200.00	mg/L
Magnesium (Mg)	65.240	mg/L
Chromium (Cr)	0.5621	mg/L
Calcium (Ca)	150.98	mg/L
Lead (Pb)	00.136	mg/L
Cadmium (Cd)	00.021	mg/L
Phosphate (PO4)	08.398	mg/L
Nitrate (NO3)	29.240	mg/L

The lab-scale anaerobic digesters were constructed using 1L glass bottles. The bottles are sealed with rubber plugs and fitted with valves for measuring biogas. Variable settings are used to operate anaerobic digesters in a batch system. Following previous research [2, 9-10] the biogas output was measured by means of the liquid displacement technique. The steps of anaerobic digestion can be seen in Figs. 3 and 4, which depict an experimental laboratory setting. Here, containers containing a barrier solution are used to transport the gases (CH_4, CO_2, N_2, and H_2S) produced by reactors. A (2%) NaOH solution, which is contained in these containers, absorbs CO_2, N_2, and H_2S. On the other hand, a graduated cylinder is used to measure the amount of CH_4 by monitoring the change in liquid levels. Finding the best circumstances for maximum cumulative methane biogas generation was the goal of the laboratory-scale experiment, which examined numerous parameters including mixing ratio, pH, temperature, and total solid content. The alkalinity and volatile fatty acid levels were monitored on a daily basis in order to determine the Acid/Total inorganic carbon-based carbon ratio (A/TIC). The goal was to keep this ratio within the optimal range of (0.1-0.4), as suggested [11-16].

Table 2. Physical and chemical properties of OFMSW

Constituent	Value
pH	5.9
Bulk density (BD)	550 kg/m3
Total solid, TS	27.11%
Volatile solid, VS	24.70%
Moisture content, MC	72.89 %
Alkalinity as (CaCO3)	1377 mg/l
Volatile fatty acid (VFA) as (CaCO3)	343 mg/l

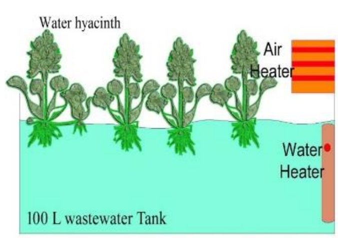

Figure 1. A schematic representation of the experimental equipment.

Figure 2. The treatment of wastewater via water hyacinth.

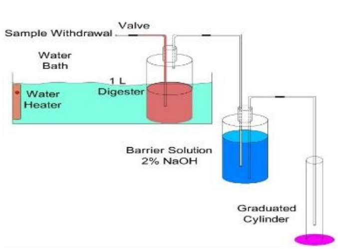

Figure 3. Lap scale anaerobic digesters schematic.

Figure 4. Lap scale anaerobic digesters.

2.3. Characterization methods

2.3.1. Physical Tests

a) Temperature:

Water temperature was measured with a graduate mercury thermometer (0-200) ºC. Air temperature was measured with an electrical thermometer.

b) Turbidity:

The nephelometric Method was used with the Lovibond TB 300 IR instrument. The measurement was made after instrument calibration with standard solutions.

c) Total Dissolved Solid (T.D.S.):

Filtering the sample with 0.45 µm filter paper. Take 10 ml from the filtered sample and dry in the oven with a temperature (of 103-105) ºC for 1 hr.

$$\boldsymbol{T.D.S\ (mg/l)} = ((\boldsymbol{A} - \boldsymbol{B}) \times (\mathbf{10})\hat{}\mathbf{6})/(\boldsymbol{sample\ volume\ (ml)}) \quad (2)$$

Where: A=Dish weight + Sample weight in grams. B=Dish the weight in grams.

d) Total Solid (T. S.):

Take 10 ml from the sample and dry in oven with temperature (103-105) ºC for 1 hr.

$$\boldsymbol{T.S\ (mg/l)} = ((\boldsymbol{A} - \boldsymbol{B}) \times (\mathbf{10})\hat{}\mathbf{6})/(\boldsymbol{sample\ volume\ (ml)}) \quad (3)$$

Where: A=Dish weight + Sample weight in grams. B=Dish the weight in grams.

2.3.2. Chemical Tests

a) pH:

pH was measured with a pH meter Orion 210 A+.

b) Biochemical Oxygen Demand (BOD)

The manometric method was used to determine the BOD5 of Samples. (250 ml) of the sample was put in a sealed container fitted with a pressure sensor, and sodium hydroxide was added to the container above the sample level. The sample was stored in the armoire thermoreglartrice, Lovibond. After five days reading was taken from the pressure sensor.

c) Nitrate (NO3)
The photometric method was used with a spectrophotometer (SP-3000 nano Optima) in (220 nm) wavelength. (50 ml) the sample was taken and added (1 ml) of HCL solution.

d) Phosphate (PO4)
The ascorbic acid method was used with a spectrophotometer (SP-3000 nano Optima) in (700 nm) wavelength. (25 ml) the sample was taken and added (5 ml) of indicator solution.

e) Chromium (Cr)
Chromium was measured using a Spectrophotometer (SP-3000 nano Optima) in (540 nm) wavelength. (250 ml) sample was taken and added (5 ml) nitric acid, (2 ml) (30%) dihydrogen dioxide for digestion. Convert Chromium (III) to Chromium (VI).

f) Lead (Pb)
Atomic Absorption Spectrophotometer (made in Japan, 2002) was used with (283.3) nm wavelength. (250 ml) was taken and added (5 ml) nitric acid, (2 ml) (30%) dihydrogen dioxide for digestion. Acetylene and clean and dry air was used for the tests.

g) Cadmium (Cd)
Atomic Absorption Spectrophotometer (made in Japan, 2002) was used with (227.8 nm) wavelength. (250 ml) was taken and added (5 ml) nitric acid, (2 ml) (30%) dihydrogen dioxide for digestion. Acetylene and clean and dry air were used for the tests.

h) Calcium (Ca)
Titration with the EDTA method was used. Take (25 ml) from the filtered sample and add (25 ml) distilled water, (2 ml) sodium hydroxide, and two drops from murexes. Then titrated with EDTA solution until the color becomes violet.

$$\boldsymbol{Ca\ (mg/l) = EDTA\ volume\ from\ titrate\ (ml) \times N\ EDTA \times M.w\ Ca \times 1000\ /\ sample\ volume\ (ml)} \tag{4}$$

i) Magnesium (Mg)
After Calcium and Hardness measurement, use the following formula:

$$\boldsymbol{Mg\ (mg/l) = EDTA\ volume\ for\ hardness\ (ml) \times EDTA\ volume\ for\ Ca\ (ml) \times 4.88} \tag{5}$$

3. Results and discussion

3.1. Wastewater treatment experiments

3.1.1. Nutrient and carbon-based Pollutants removal

The findings of this study demonstrate the capacity of water hyacinth to effectively eliminate nutrients and carbon-based compounds from municipal wastewater. The lowest levels of biochemical oxygen demand (BOD_5), phosphate (PO_4), nitrate (NO_3), and turbidity in the treated wastewater were observed on the (17th day) for BOD_5, nitrate, and phosphate, and on the (14th day) for turbidity. The recorded concentrations were (1.716 mg/L) for nitrate, (2.028 mg/L) for phosphate, (0 mg/L) for BOD_5, and (2.24 NTU) for turbidity. The removal efficiency for each parameter was (94.1%, 75.8%, 100%, and 93.8%) respectively. The concentration of effluent for NO_3, BOD_5, and Turbidity is below the maximum permissible concentration of (15, 5 mg/L, and 10 NTU) respectively, as specified by the Iraqi regulations for protecting rivers from pollution (Iraqi determinants of rivers maintenance system from pollution 1967). The removal of nutrients takes place through two methods. Firstly, it involves the actions of microbes like nitrification and denitrification, which are present in the roots of water hyacinth. Secondly, it involves the absorption of nutrients by the plant itself [17-19] showing that during times of intense photosynthetic activity, the presence of water hyacinth in wastewater could reduce the concentration of dissolved CO_2 [20]. Photosynthetic processes raise the concentration of oxygen (O_2) in water. As a result, the biological oxygen demand (BOD) is reduced, and aerobic bacterial activity is fostered in the effluent. These results are consistent with other studies that validate the capacity of aquatic plants to utilize nutritional molecules present in wastewater [21]. Figures 5, 6, 7, 8, and 9 depict the temporal changes in the concentration and removal efficiency of NO_3, PO_4, BOD_5, and turbidity.

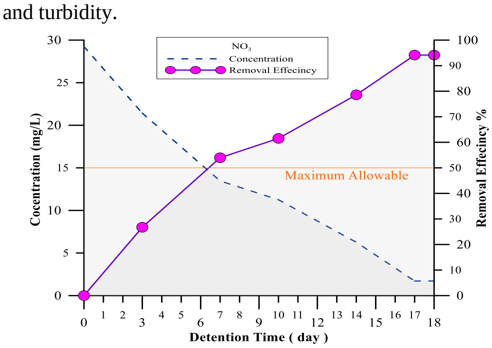

Figure 5. The relationship between reduction in nitrate concentration and removal efficiency.

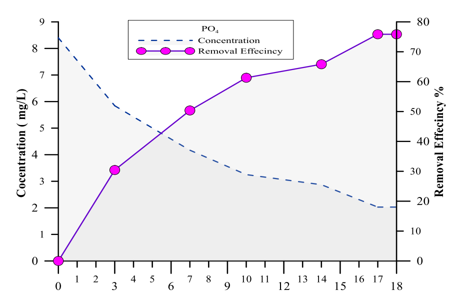

Figure 6. The relationship between reduction in phosphate concentration and removal efficiency.

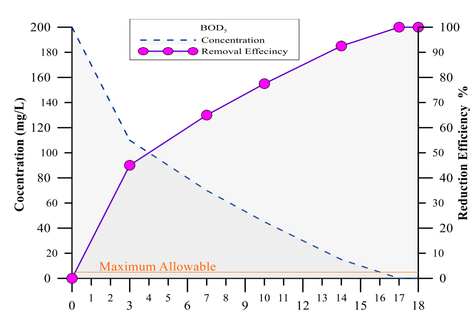

Figure 7. The relationship between biochemical oxygen demands concentration and removal efficiency.

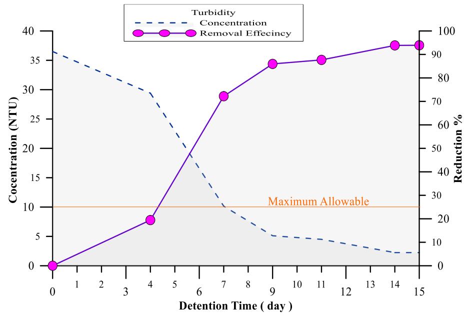

Figure 8. The relationship between reduction in turbidity and removal efficiency.

3.1.2. *Heavy metals removal*

The minimum concentrations of lead (Pb), chromium (Cr), and cadmium (Cd) were recorded on the (13th day) as (0.007 mg/L, 0.032 mg/L and 0.0019 mg/L) respectively. The removal effectiveness of lead (Pb), chromium (Cr), and cadmium (Cd) was (94.9%, 94.31 %, and 91.3%) respectively. The effluent concentration is below the permissible limit for discharge into the river, as specified in the variables in Iraq that affected the river pollution prevention system in 1967. The maximum acceptable concentrations are (0.1 mg/L, 0.1 mg/L, and 0.1 mg/L) respectively. The elimination of water hyacinth is mostly attributed to its ability to immobilize metals, which is the most prevalent process contributing to its conditioning. Water hyacinth is capable of reducing heavy metals by producing Thio-containing cation chelating chemicals such as Glutathione (GSH) in response to heavy metal exposure that occurs through the cytoplasm (Symplast route) [22-23]. The presence of cadmium leads to an increase in chelators in the root and leaves of water hyacinth [24]. These results are consistent with findings from several researchers. Figures 9, 10, and 11 display the concentration and efficacy of removal.

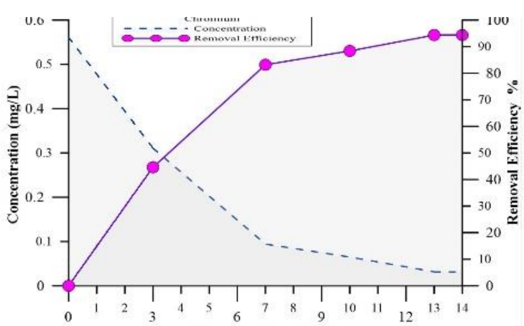

Figure 9. The relationship between reduction in chromium and removal efficiency.

3.1.3. Decrease in hardness

On the (25th day), the calcium (Ca) concentration was tested to be (85.45 mg/L) and the magnesium (Mg) concentration was recorded to be (37.1 mg/L). The removal efficiency for calcium was (41.42%) and for magnesium was (43.13%). The concentration of the effluent is below the permissible limit for discharge into the river, with values of (200 mg/L and 150 mg/L), as stated in the Iraqi regulations for maintaining river quality and preventing pollution in 1967. As depicted in Figs. 12, and 13. Calcium and Magnesium are vital elements for plant growth. This is an explanation of why these two items were deleted with a respectable percentage.

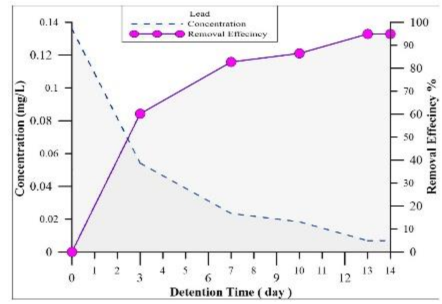

Figure 10. The relationship between reduction in lead and removal efficiency.

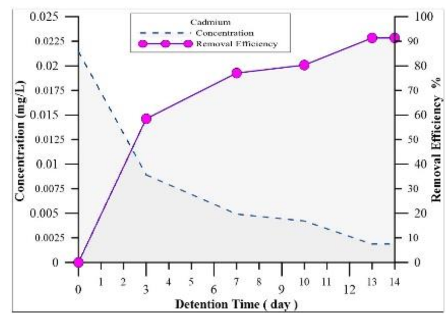

Figure 11. The relationship between reduction in cadmium and removal efficiency.

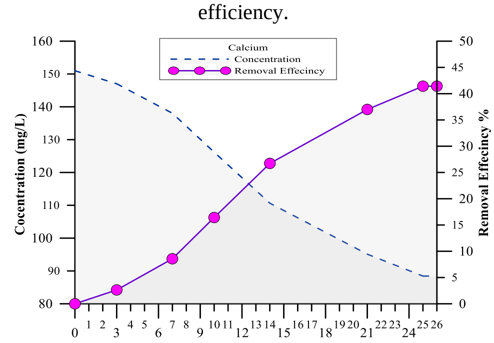

Figure 12. The relationship between reduction in calcium and removal

3.1.4. Variation in pH

Figure 14 illustrates the pH changes seen during the treatment process. The pH level at the end of the 16-day experiment ranged from 7.44 to 7.82, which falls within the natural range. The decrease in pH is caused by the influence of acidity-buffering components such as HCO3 and CO2. The buffer capacity of aquatic plants allows them to mitigate the effects of water acidity. The buffer capacity of water hyacinth is achieved through the exchange of negative and positive ions, which helps maintain balance in the aquatic environment [25]. The pH reduction process observed in this study has a beneficial environmental impact as it helps decrease the toxicity of certain heavy metals. Furthermore, it helps with the process of reducing complicated mineral and elemental compounds to simpler ones that water hyacinth can absorb more easily. Stottmeister, [13] found that microbes that grow at certain pH levels facilitate this conversion.

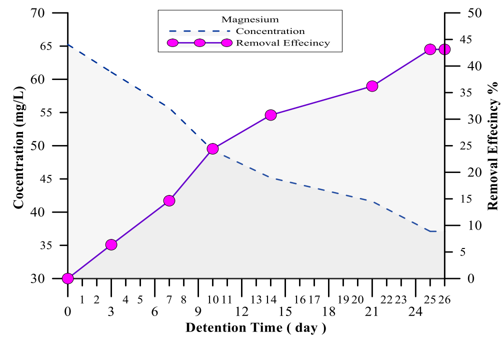

Figure 13. The relationship between the reduction of magnesium concentration and removal efficiency.

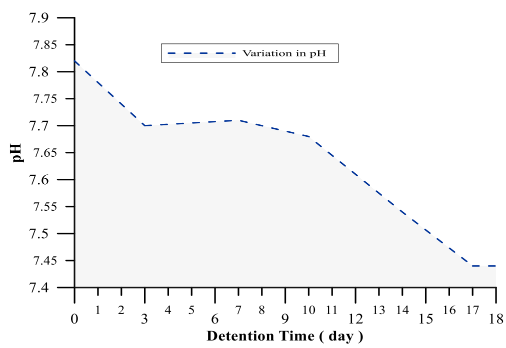

Figure 14. Variation in pH value.

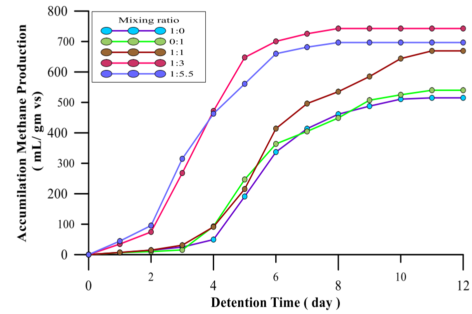

Figure 15. The cumulative methane generation from various WH/OFMSW ratios at pH=6.3 and TS =9.5.

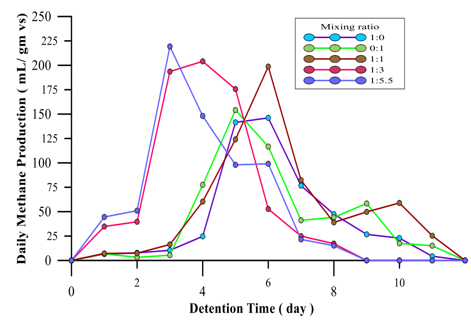

Figure 16. Daily methane generation from various WH/OFMSW ratios at pH=6.3 and TS =9.5.

3.2. Methane Biogas Production

3.2.1. Effect of WH /OFMSW mixing ratio

The influence on methane production of the water hyacinth (WH) to the organic fraction of municipal solid waste (OFMSW) mixing ratio is shown in (Figures 15 and 16). (Figures 15 and 16) show the results showing the maximum methane output. The total amount of methane produced is (742.63 mL/gm) of volatile solids (v.s.) when wood hydrolysate and organic fractions of municipal solid waste (WH/OFMSW) are mixed at a ratio of (1:3). For other ratios of (0:1, 1:0, 1:1, and 1:5.5), the methane productions are (539.97, 515.02, 669.22, and 696.73 mL/gm v.s), respectively. At various time intervals, the highest daily methane production was observed for ratios of (0:1, 1:0, 1:1, 1:3, and 1:5.5) respectively. These points occurred at (5, 6, 6, 4, and 3) days after the experiment. The corresponding methane productions were (154.16, 146.12, 198.67, 204.07, and 219.3) mL/gm v.s. Hence, the optimal ratio of (1:3) will be employed in subsequent studies. The rationale behind selecting this ratio is to achieve a harmonious equilibrium between the carbon-to-nitrogen (C/N) ratio. If the (C/N) ratio is lower or higher than the required ratio, it may result in a decrease in production. A high carbon-to-nitrogen (C/N) ratio can result in the quick use of nitrogen by methanogens, leading to a reduction in gas output. Conversely, a low carbon-to-nitrogen ratio results in pH levels surpassing (8.5) and the buildup of ammonia, which is harmful to methanogenic bacteria [20].

3.2.2. Effect of pH

The pH of a mixture of wastewater and organic fraction of municipal solid waste (OFMSW) was adjusted within the range of (6.5, 7, 7.5, 8, and 8.5) using either (0.1 M) sulfuric acid (H_2SO_4) or (0.1 M) sodium hydroxide (NaOH). The temperature and TS were set at a fixed value of (20±2 ^{o}C) and (9.49%) respectively. The mixing ratio is set at the optimal value of (1:3), which was determined in a prior experiment. The trials are conducted until methane generation ceases or reaches a minimum, typically occurring after a duration of (9 days). Methane production takes place at a pH of (7.5), reaching a maximum value of (820.62 mL/gm v.s), as depicted in (Figure 17). The peak daily methane production of (208.09 mL/gm) is observed on the (4th day), as depicted in Fig. 18. The optimal pH range for the growth of methanogenic bacteria, which are responsible for methane production, is typically specified as (6.5-8.2) [1]. This may explain why this particular pH level is considered the optimum. The anaerobic digestion process is influenced by variations in pH due to the direct impact of hydrogen ion concentration on microbial development. The optimal pH for the growth rate of methanogens will be significantly diminished if it falls below a pH of (6.60). A pH below (6.10) or above (8.30) will result in suboptimal performance and potential failure of the digester [11]. Therefore, it is imperative to rectify the imbalanced and acidic pH state in the digester. The methane biogas process is more susceptible to changes in pH due to the increase in free ammonia concentration when pH increases, which might hinder bacterial activity [7]. Consequently, a pH of (7.5) was retained for further trials.

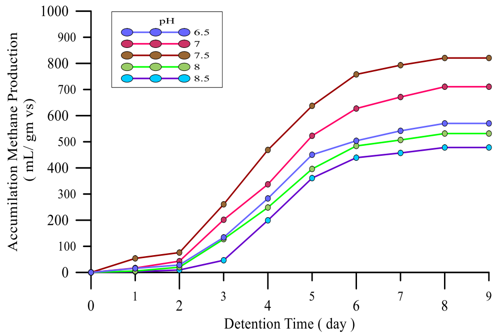

Figure 17. Methane accumulation at various pH levels, mix ratio = 1:3 and TS=9.5.

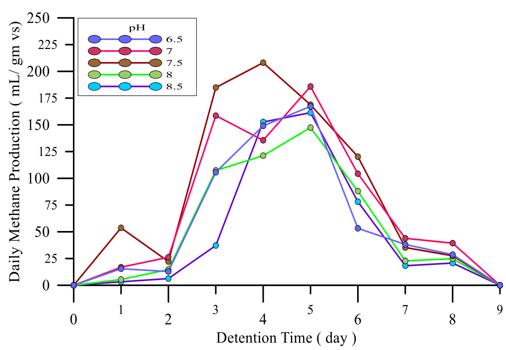

Figure 18. Daily methane generation at various pH, mix ratio = 1:3 and TS=9.5.

3.2.3. Effect of temperature

The study investigated the impact of various temperature values (25, 30, 35, and 40 ºC) on methane production, considering mixing ratio and pH values. The concentration of total solids is set at a constant level of (9.5%). The optimal temperature for optimum methane production was determined to be (35°C), resulting in an accumulative methane yield of (926.89 mL/gm v.s). The generation of methane at temperatures of (25, 30, and 40 ºC) is (645.32, 732.46, and 885.55 mL/gm v.s), respectively, as depicted in Fig. 19. At temperatures of (25, 30, 35, and 40 ºC), the highest daily methane production is observed on the fourth day. The corresponding methane productions are (187.86, 181.55, and 273.9 mL/gm v.s), as depicted in Fig. 20. Multiple researchers have discovered that mesophilic bacteria are mostly responsible for methane generation. The mesophilic level ranges between (25 and 40 ºC). The methanogenic activity exhibited a high degree of sensitivity to temperature. When the temperature exceeds a specific threshold (i.e., 35 ºC), the methanogenic activity diminishes, hence reducing the activity of the bacteria responsible for methane formation (Yogita et al., 2012). Consequently, the temperature was set at this specific value for further trials.

3.2.4. Effect of Total solid (T.S)

The impact of TS was examined at the optimal conditions of a mixing ratio of (1:3), a pH of (7.5), and a temperature of (35 ºC), which were determined from earlier tests. The T.S (Total Solids) varies within the range of (7%-12%) added by (1). The highest cumulative methane production is observed at a TS percentage of (10%), with a production rate of (1039.80 mL/gm v.s), as indicated by Fig. 21. The highest daily methane production, as depicted in Fig. 22, is observed on the (4^{th} day) for total solids (TS) concentrations of (7%-9%), 3rd for total solids (TS) concentrations of (10%) and (5^{th} day) for total solids (TS) concentrations of (12%). The corresponding methane productions are (131.5, 196.48, 300.95, 286.59, 322.43, and 138.05 mL/gm v.s). The total sulfur (TS) concentration increased to (3.2%) during an (8^{th} day) reaction time, with approximately (59.8%) of the reaction consumed, as depicted in Fig. 23. This indicates the extent of the reaction occurring in the anaerobic digester.

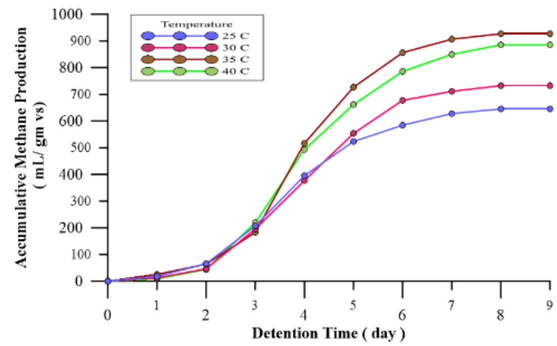

Figure 19. Methane accumulation at various temperatures, pH = 7.5, mix ratio = 1:3, and TS =9.5.

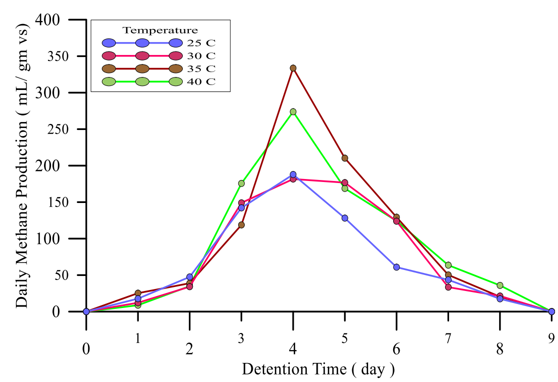

Figure 20. Daily methane generation at various temperatures, pH = 7.5, mix ratio = 1:3and TS=9.5.

The presence of non-degradable volatile solids in the form of lignin can prevent a high biogas yield, even if the substrates have a high volatile solid concentration (i.e., 11 and 12%). The volatile matter content of any substrate refers to the proportion of solids that is converted into methane biogas. Therefore, to achieve effective digestion, it is necessary to utilize anaerobic digestion of water hyacinth and carbon-based wastes using thickening sludge as a source of bacteria. This procedure ensures a proper balance between the lignin content and the carbon-to-nitrogen ratio [12]. Furthermore, as the TS percentage rises, the water percentage drops, leading to a decline in microbial activity. This, in turn, has an impact on the quantity of biogas produced, especially at higher TS values [24]. The Figures indicate that when the solid concentration exceeds the recommended percentage of 11% of total solids, as stated by [9] methane production decreases or drops significantly. This finding aligns with the results of the current study.

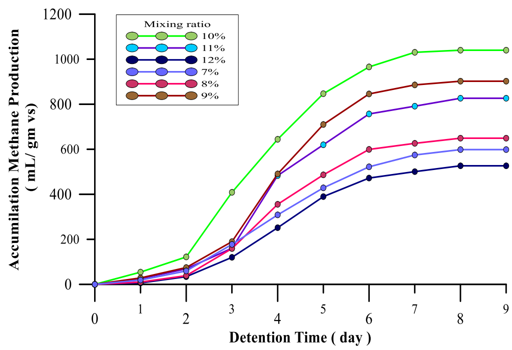

Figure 21. Methane accumulation at various total solid content, pH=7.5, mix 1:3 and Temp.=35 ºC.

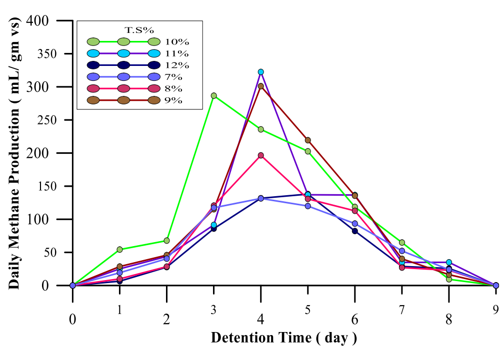

Figure 22. Daily methane generation at various total solid content, pH=7.5, mix 1:3 and Temp.=35 ºC.

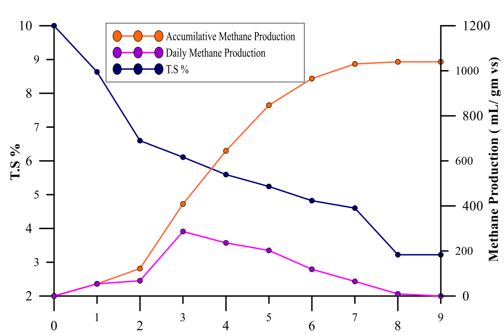

Figure 23. TS percentage reduction with daily and accumulative methane generation.

In 2012, Subramani and Nallathambi conducted a study to determine the methane fraction produced from the anaerobic digestion of a mixture of kitchen waste and sewage water. They found that the methane fraction was (65%). The findings of this study suggest that the utilization of public solid waste is superior to that of kitchen garbage. This could be attributed to the larger percentage of carbon sources in public solid trash, which is likely related to the significant prevalence of paper and wood. Meanwhile, [23] determined that the methane content in cow dung from WH was (24%).

The parameter that had the greatest impact on anaerobic digestion was the total solid percentage (T.S%), which increased production by up to (49.36%). When all parameters (mixing ratio, pH, temperature, and total solid) were adjusted to their optimal conditions, the overall production increased by (50.5%), as illustrated in Figs. 24 and 25.

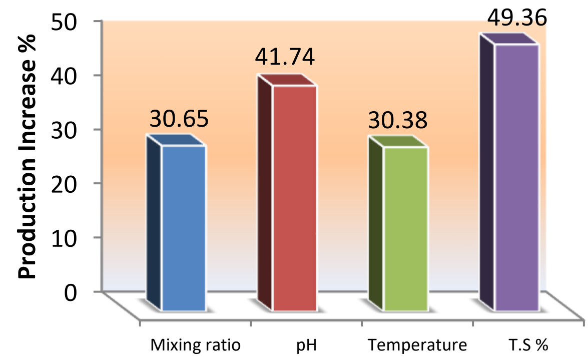

Figure 24. Methane production increase percentage.

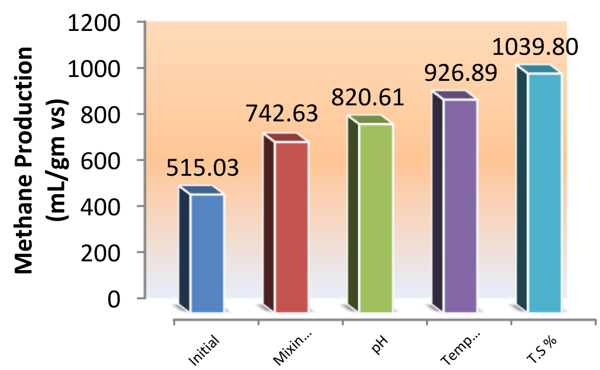

Figure 25. After adjusting for several conditions, methane production increased.

3.2.5. Total Volatile Acids and Total Alkalinity

The stability of the anaerobic digestion process was assessed under optimal conditions, which were achieved with a mixing ratio of (1:3), a pH of (7.5), a temperature of (35 ºC), and a total solids content of 10%. The combination of VFAs and alkalinity serves as reliable indications for assessing the stability of the anaerobic reactor.

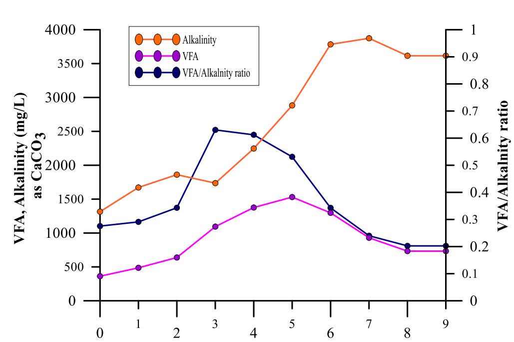

Figure 26. Differences in VFA to alkalinity ratio.

The obtained ratio ranges from 0.20 to 0.63. The process appeared stable due to the absence of any accumulation of volatile fatty acids (VFAs). According to a prior study conducted by [19], it was found that if the ratio of volatile fatty acids (VFAs) to alkalinity exceeds (0.80), it leads to the suppression of methanogens, which are responsible for methane generation. Additional studies conducted by Sanchez et al. (2005) and Malpei et al. (1998) have indicated that the ideal average ratio of volatile fatty acids (VFAs) to alkalinity should not exceed (0.40) and should not fall below (0.1). This aligns closely with the average ratio observed in the current study, which was (0.3854). (Figure 26) illustrates the relationship between the concentration of volatile fatty acids (VFAs) and the alkalinity ratio.

3.2.6. *Multiple correlations for methane production process*

The study utilized the multiple correlations methodology to determine the relationship between methane generation and the optimal mixing ratio, pH, temperature, and total solid content. Equation ($y=aX_1^bX_2^c X_3^d X_4^e X_5^f$) was solved to find out these relationships by the application of Excel program. The coefficients of the independent variables can be determined based on the experimental data. The correlation coefficient (R^2) is determined to be (91.36%). An ideal (R^2) value is approximately 1, indicating a strong connection between the experimental and projected values. The highest methane generation achieved in the experiment under optimal conditions, including a mixing ratio of (1:3), pH of (7.5), temperature of (35) degrees Celsius, and total solid content of (10), is similar to that obtained through repeated correlations. The equation obtained is as follows:

$$y = 247.2066 \times (X_1^{-0.77881} \times X_2^{-0.02794} \times X_3^{0.58360} \times X_4^{0.45149}) \qquad (6)$$

Where:

y: Generated methane accumulation (mL/gm v.s), X_1: pH, X_2: mixing ratio, X_3: total solid (%), X_4: temperature (°C), y theoretical: (1013.017 mL/gm v.s.), computed from the equation using multiple correlations; y practical: (1039.80 mL/gm v.s.) derived from a lab-scale anaerobic digester.

4. Application of Gompertz and first-order kinetic models

Gompertz and first-order kinetic models are used to model the experimental data on cumulative methane generation. Both (Table 3) and (Figures 27 and 28) show the results. Using EXCEL-2010 and non-linear regression, we identified the model parameters.

Table 3. Gompertz parameters and first-order kinetic model parameters.

	B, (mL/gm)	Rb, (mL/gm)	λ, days	R^2
Gompertz model	1083.088	272.72	1.533	0.999
Investigational	1039,80	286,596	1	----
Kinetic model of the first-order	K, 1/day		R^2	
	- 0.2364		0.9971	

Based on the data presented in Figs. 27 and 28, as well as Table 3, the following conclusions can be listed:

1. The Gompertz model exhibited a strong match with the experimental data, displaying a high correlation coefficient. The measured values for the experimental methane production potential (B, mL/gm v.s), maximal biogas production rate (Rb, mL/gm v.s/day), and lag phase (λ, days) closely align with the values predicted by the applied model. The acquired results are matched with empirical data. (Table 4) presents a comparison of data gained from the current investigation and data gathered by other researchers using the Gompertz model.

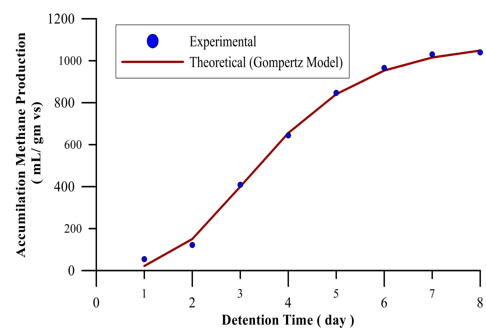

Figure 27. Evaluation of the methane production process using experimental data and the revised Gompertz model.

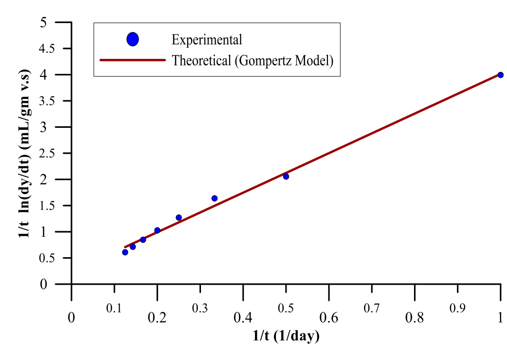

Figure 28. Methan generation experimental data compared to first-order kinetic model.

Table 4. Using the Gompertz model, we compare the results of this study to those of other researchers.

Type of waste	Measured value mL/gm V.S	*B*, mL/gm v.s	*Rb*, mL/gm v.s	λ, days	R^2	Reference
WH/OFMSW	1039.80	1083.09	272.72	1.533	0.999	Present
Wastewater	111.649	109.37	23.466	0.803	0.988	[4]
Water Hyacinth Using Poultry Litter	480	449.4	27.9	6.625	0.98	[9]
Horse and cow dung	353	360	36.99	8.07	0.997	[24]
Water hyacinth and primary sludge	350	358	13.7	10.462	0.998	[13]
MSW	489	482	72	1.7	0.995	[25]

2. In this study, the biodegradability of WH/OFMSW was evaluated using a mathematical model that relied on first-order kinetics. The term (-k) quantifies the speed at which the biodegradable components are eliminated, whereas the production of biogas grows over time. The negative value obtained (-0.2364) suggests a rapid biodegradation of solid waste. This also verifies that the ideal circumstances for biodegradation, including the mixing ratio of waste household and organic fraction of municipal solid waste (WH/OFMSW), pH level, temperature, and total solids percentage (T.S%), enhance the efficiency of the anaerobic digestion process. This is inconsistent with the results achieved by Yusuf in 2011.

5. Conclusions

This investigation confirmed the effective utilization of water hyacinth for wastewater treatment and biogas production in a straightforward method that can be implemented in local settings and aligned with the environmental principle of maximizing resource utilization while minimizing waste discharge. Considering the experimental findings and theoretical models used in a laboratory-scale system, the following conclusions were inferred. The water hyacinth treatment system demonstrated its capacity to eliminate nitrogen and carbon-based contaminants in wastewater treatment, with the removal efficiencies for nitrate (NO_3), phosphate (PO_4), biological oxygen demand (BOD_5), and turbidity being 94.13%, 75.85%, 100%, and 93.86% correspondingly. The removal efficiencies for lead (Pb), chromium (Cr), and cadmium (Cd) were 94.93%, 94.35%, and 91.33% respectively. For calcium (Ca) and magnesium (Mg), the percentages were 41.42% and 43.13% correspondingly. Furthermore, the highest level of methane accumulation in methane biogas generation was achieved under optimal conditions, specifically a ratio of 1:3 for WH/OFMSW, a pH of 7.5, a temperature of 35 degrees Celsius, and a total solids content of 10%. The multiple correlations equation was used and yielded an acceptable correlation coefficient value, indicating a strong connection between the experimental and predicted values. The R^2 value was 91.36%. The high correlation coefficient demonstrated that the Gompertz model closely matched the experimental data. It appears that the biodegradation of the solid waste happened quite quickly since the biodegradation rate constant (k) calculated using first-order kinetics was negative.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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