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Investigate the Operating Temperature Effect on Fast Pyrolysis Products of Food Waste with Hydrogen

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Energy crises and environmental pollution are the main issues of concern all over the world and the disposal of wastes by converting into gaseous products can reduce this to a level. Investigating how operating temperature affects the yield and makeup of bio-oil, bio-char, and bio-gas during the pyrolysis process in the presence of hydrogen is the goal of this study. By offering a novel method for enhancing the quality and yield of gaseous products through controlled thermal decomposition in a hydrogen-enriched environment, the findings improve sustainable technologies. In this research, the fast pyrolysis of food waste carried out by using a lab scale fixed bed reactor in the presence of different composition of Nitrogen and Hydrogen to investigate the effect of operating parameters high pyrolysis temperature 600, 650, 700, 750 and 800 °C and hydrogen gas 0 %, 10 % and 20 % with Nitrogen as a carrier gas. The gaseous products maximum yield i.e. 45.68 comes out at 750 °C temperature in the presence of 10 % hydrogen. The results indicate that increasing the pyrolysis temperature boosts decomposition reactions, encouraging the formation of gaseous products. Hydrogen plays a crucial role by facilitating cracking and stabilizing the reaction intermediates, minimizing the formation of heavier components. The results demonstrate that the fast pyrolysis of food waste give residue at high temperature and in the presence of hydrogen up to 10 % achieved a maximum the bio gas yield. Energy crises and environmental pollution are major global concerns. Converting waste into gaseous products can help address these issues. This study examines how operating temperature influences the yield and composition of bio-oil, bio-char, and bio-gas during pyrolysis in a hydrogen-rich environment. By introducing a novel approach to enhance the quality and yield of gaseous products through controlled thermal decomposition, the findings contribute to sustainable technologies. The research involves fast pyrolysis of food waste using a lab-scale fixed-bed reactor, with varying nitrogen and hydrogen compositions. The effects of different operating parameters were analyzed, including high pyrolysis temperatures (600, 650, 700, 750, and 800 °C) and hydrogen concentrations (0%, 10%, and 20%), with nitrogen as the carrier gas. The highest gas yield (45.68%) was achieved at 750 °C in the presence of 10% hydrogen. The results show that increasing pyrolysis temperature enhances decomposition reactions, leading to higher gas production. Hydrogen plays a key role by promoting cracking reactions and stabilizing reaction intermediates, reducing the formation of heavier byproducts. The study demonstrates that fast pyrolysis of food waste at high temperatures, with up to 10% hydrogen, results in the highest bio-gas yield.

Keywords: Food Waste, Fast Pyrolysis, Hydrogen, Gaseous Products, Yield.

Introduction:

The major issue of food waste has become a worldwide problem due to its environmental concerns, social implications and economic issues. According to the Food and Agriculture Organization (FAO) it has been observed that around one by third of all produced food from consumption of humans, annually amount of wastage is approximately 1.3 billion tons. This significant amount of wastage is not only showing a substantial loss of resources like energy, food land, and sea water, but it can cause various dangerous environmental problems by contributing in it [1]. Food waste is compositionally unique, containing higher organic compounds like carbohydrates and proteins to produce gaseous products by fast pyrolysis in the presence of hydrogen to prevent waste management and promote renewable energy. By addressing all these issues, it has been very developing interest in reconnoitering the such management plans for sustainable wastage of all organic things, that it should be converted the all waste of food into valuable products, consequently it can promote a globular economy and can reduced the environmental issues [2].

One of the fastest approaches of this fact is the conversion of food waste thermochemical through fast pyrolysis, but particularly with main focus on maximizing the production of biogas by it. Pyrolysis is a thermochemical process which involves the thermal decomposition of organic materials at high temperatures in the absence of oxygen [3]. The results of this process is in the production of many products such as bio-oil, bio char, and gaseous products. The large dependency of products distributions is on the operating conditions. Among the various types of pyrolysis, the fast pyrolysis is distinguished from all its various types due to its rapid reaction rates and short time of vapor residence. So ultimately it optimized to enhance the yield of liquid bio-oil [4]. However, in recent years, the demand of biogas is increase day by day, so it has been interesting in increment the production of gaseous products, which is the huge source renewable energy [5]. Therefore, to optimize the operating parameters of fast pyrolysis to enhance the production of biogas is the basic factor of research, by utilizing food waste as a feedstock. To obtain the efficiency of the pyrolysis process and the yield of required products, such as gaseous products, are significantly partial by different operating parameters, such as operating temperature, composition of feedstock, and the existence of reactive gases [6]. The top rich factor is temperature, which is known to play a critical role in the pyrolysis reaction process, so it can cause a huge affecting aspect in the distribution of bio-char, bio-oil, and gaseous products [7]. It has been studying that higher pyrolysis temperatures generally favor to the formation of bio-oil and gaseous products, while lower temperatures cause the higher rate the production of bio-char.

But the bio-oil production yield decreases after increasing the temperature than that optimum temperature. For example, at temperatures between 600 °C and 800 °C, the gas production rate is increased in higher peak, by enhance the yields of methane and other hydrocarbons. For fast pyrolysis of wastage of food, the temperature range is particularly relevant with it. It allows the thermal cracking of complex organic compounds, to the release of volatile gases such as biogas as compared to other products. During pyrolysis process, the temperature rises and the introduction of hydrogen, it has been examined to better the quality and yield of the making products. By hydrogen adding during pyrolysis process, hydrogen-involved or hydro pyrolysis, can improve the making of gaseous products by promotes the hydrogenation and cracking reactions [8]. The involvement of hydrogen is introduced to provide the large molecular structures, thereby the making of lighter hydrocarbons and biogas products. Moreover, by the addition of hydrogen in the elimination of oxygen from the organic compounds that involves in food waste, leads to result in rising the calorific value of gaseous components.

Except the potential benefits of hydrogen- assisted pyrolysis, there is a minimum research on food waste application, specifically with biogas making products. The advanced study of this system that involves effective combination of temperature and the concentration of hydrogen on the food pyrolysis waste, with a main focus on the yield of biogas. The experimental process that includes how to conduct pyrolysis reactions at different temperatures and hydrogen concentrations. So, this experiment involves the conducting pyrolysis reactions at various temperatures (600 °C, 650 °C, 700 °C, 750 °C and 800 °C) and by using different hydrogen volume concentrations (0 %, 10 %, and 20 %). By finding these key parameters, the study focused on find the impact on pyrolysis products distribution especially with the gaseous products formation. The method of incrementally rising the hydrogen concentration gives a deep knowledge of how hydrogen affects the reactions of pyrolysis, especially in improving the yield of methane and other combustible gases [6]. Studies and research on pyrolysis has mainly focused on production of biomass, such as wood and wastage of agricultural residues, and significantly different in composition from food waste. Food waste is produced by a higher moisture content with using complex ingredients such as carbohydrates, fats, proteins, and various inorganic compounds [9].

The differences between composition results to form in separate behaviors of thermal degradation, for enhance the required approach to improve the pyrolysis process for food waste. To remove of all diverse compounds, the adding of hydrogen during the process of pyrolysis having the influence effect, which can cause potentially prominent to enhance the yields of respected gaseous products. For example, it has been observed that the assisted based hydrogen pyrolysis could be meaningfully enhance the yield of methane by breaking down the bonds of C–O and C–C [10]. Consequently, it established that the presence of hydrogen can change the product circulation of hydrocarbons, to enlightening the overall energy of the pyrolysis gases by pyrolysis process.

The motivation for this study is boosted to develop efficient energy from waste by using various technologies that can convert food waste into renewable energy sources, and improve the environment. To increase biogas production, it is optimizing the fast pyrolysis process. This research aims to eliminate the environmental impacts of food waste removal, so we can use some solutions including development of sustainable energy and reduce dependence on fossil fuels [11]. The results of this study have significant applications for the proposal of pyrolysis systems, particularly by adding the hydrogen-based processes, which are gaining more attention to upgrade the quality of pyrolysis process. Moreover, by understanding the higher effects of temperature and hydrogen concentration on food waste pyrolysis which are providing valuable impacts for enhance the technology and mixing it into current waste systems [12]. This study not only increase the impact of different temperatures and hydrogen concentrations on the pyrolysis of food waste, but it also has main focus on production of biogas as the main valuable and interesting product. The experimental results having main focus to demonstrate the increment of thermal decomposition of food waste by using hydrogen in the process to obtain the higher yield of gaseous product as methane-rich product [13]. To increase the circular economy and to promote sustainable waste management, some focused practices and efforts are required to fulfil this target by converted the waste materials into valuable products. By understanding of these operating parameters that can cause the biogas production from food waste, so this research could the main approach for the development of optimized pyrolysis process system for producing clean and renewable energy from organic waste compounds [14].

The issue of food waste has become a global concern due to its environmental, social, and economic implications. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced for human consumption is wasted annually, amounting to around 1.3 billion tons. This significant wastage not only results in a substantial loss of resources such as energy, land, and water but also contributes to various environmental problems [1]. Food waste is compositionally unique, containing high amounts of organic compounds like carbohydrates and proteins. These compounds can be converted into gaseous products through fast pyrolysis in the presence of hydrogen, providing an effective solution for waste management and renewable energy production. Addressing these issues has sparked growing interest in sustainable waste management strategies, particularly in converting food waste into valuable products. This approach promotes a circular economy and reduces environmental impact [2].

One of the most efficient methods for converting food waste is thermochemical conversion through fast pyrolysis, with a primary focus on maximizing biogas production. Pyrolysis is a thermochemical process that decomposes organic materials at high temperatures in the absence of oxygen [3]. This process yields bio-oil, biochar, and gaseous products, with product distribution largely dependent on operating conditions. Among different pyrolysis techniques, fast pyrolysis is particularly notable for its rapid reaction rates and short vapor residence times, optimizing the yield of liquid bio-oil [4]. However, in recent years, the demand for biogas has increased significantly, leading to a growing interest in enhancing the production of gaseous products, a major source of renewable energy [5]. Thus, optimizing the operating parameters of fast pyrolysis to enhance biogas production is a key research focus, utilizing food waste as feedstock. The efficiency of the pyrolysis process and the yield of gaseous products are significantly influenced by parameters such as operating temperature, feedstock composition, and the presence of reactive gases [6].

Temperature plays a critical role in pyrolysis, significantly affecting the distribution of biochar, bio-oil, and gaseous products [7]. Studies have shown that higher pyrolysis temperatures generally favor the formation of bio-oil and gaseous products, while lower temperatures lead to increased biochar production. However, beyond an optimal temperature, bio-oil yields tend to decrease. For instance, at temperatures between 600°C and 800°C, gas production peaks, enhancing yields of methane and other hydrocarbons. In food waste pyrolysis, this temperature range facilitates the thermal cracking of complex organic compounds, leading to the release of volatile gases such as biogas [8]. Introducing hydrogen during pyrolysis has been examined as a method to improve product quality and yield. Hydrogen-assisted pyrolysis, or hydro-pyrolysis, enhances gaseous product formation by promoting hydrogenation and cracking reactions [9]. The addition of hydrogen facilitates the breakdown of large molecular structures, increasing the production of lighter hydrocarbons and biogas. Furthermore, hydrogen helps remove oxygen from organic compounds in food waste, increasing the calorific value of the gaseous components. Despite the potential benefits of hydrogen-assisted pyrolysis, limited research has been conducted on its application to food waste, particularly in biogas production [10].

This study aims to explore the effects of temperature and hydrogen concentration on food waste pyrolysis, focusing on biogas yield optimization. The experimental process involves conducting pyrolysis reactions at different temperatures (600°C, 650°C, 700°C, 750°C, and 800°C) using varying hydrogen concentrations (0%, 10%, and 20%). By analyzing these key parameters, the study investigates their impact on product distribution, particularly gaseous products. Incrementally increasing hydrogen concentration provides insight into how hydrogen affects pyrolysis reactions, particularly in enhancing methane and other combustible gas yields [11]. Most previous studies on pyrolysis have focused on biomass sources such as wood and agricultural residues, which differ significantly in composition from food waste. Food waste typically has higher moisture content and complex components, including carbohydrates, fats, proteins, and inorganic compounds [12]. These compositional differences lead to distinct thermal degradation behaviors, necessitating an optimized approach for food waste pyrolysis. The addition of hydrogen during pyrolysis has a notable influence, potentially improving the yield of desired gaseous products. For example, hydrogen-assisted pyrolysis has been shown to enhance methane yield by breaking C–O and C–C bonds [13].

The motivation for this study is to develop efficient waste-to-energy technologies, converting food waste into renewable energy sources while reducing environmental impact. Optimizing the fast pyrolysis process for increased biogas production contributes to sustainable waste management, reducing dependence on fossil fuels. The findings of this study have significant implications for designing advanced pyrolysis systems, particularly those incorporating hydrogen-assisted processes to enhance biogas production. Additionally, understanding the effects of temperature and hydrogen concentration on food waste pyrolysis provides valuable insights for improving pyrolysis technology and integrating it into existing waste management systems [14]. This research not only examines the impact of different temperatures and hydrogen concentrations on food waste pyrolysis but also focuses on biogas production as the primary valuable output. The experimental results demonstrate the enhanced thermal decomposition of food waste through hydrogen addition, leading to higher methane yields. To promote a circular economy and sustainable waste management, further research and practical applications are required to convert waste materials into valuable products. Understanding these operating parameters can help optimize pyrolysis systems for producing clean and renewable energy from organic waste [15].

Objectives of the Study:

The study aims to contribute to sustainable waste management by converting food waste into valuable energy-dense gaseous products. The specific objectives are as follows:
This study aims to support sustainable waste management by transforming food waste into valuable, energy-rich gaseous products. The specific objectives are as follows

- To analyze the impact of pyrolysis temperature (600–800°C) on the yield and composition of bio-oil, bio-char, and biogas.
- To evaluate the role of hydrogen in enhancing biogas production and improving gas composition, particularly CH_4 and H_2 content.
- To compare the product distribution of hydrogen-assisted pyrolysis with conventional nitrogen-assisted pyrolysis.
- To study how pyrolysis temperature (600–800 °C) effects the yield % biogas.
- To assess the role of hydrogen in increasing biogas production and improving its composition, especially CH_4 and H_2 levels.

To provide insights into the reaction mechanisms involved in hydrogen-assisted pyrolysis, including hydrocracking and gasification pathways. To explain the reaction mechanisms in hydrogen-assisted pyrolysis, including hydrocracking and gasification pathways.

Material and Methods:

Collection and preparation of feed stock:

The food waste samples obtained from the cafeteria of University of Gujrat, main campus for experimentation. Our food waste samples consist of mainly fruits and vegetables peel (potatoes, mango and banana). The food waste was physically sorted after it was collected in order to eliminate any non-organic pollutants like paper or plastic. After that, it was carefully cleaned with distilled water to get rid of any remaining debris. In order to maximize the surface area for effective drying, the bigger pieces were manually broken into tiny fragments using a stainless- steel cutter after washing. After being equally distributed on stainless steel trays, these pieces were allowed to cure for around 10 days in the open air.

The natural loss of moisture throughout the drying process decreased the feedstock's total water content. The samples were periodically turned over during this time to guarantee even drying and stop microbiological development. Once the drying process was complete, the samples were further processed to achieve a uniform particle size. They were ground using a mechanical grinder and then sieved to obtain particles of consistent size. The prepared feedstock was stored in airtight containers to prevent moisture absorption before further experimentation.

The food waste samples used in this experiment were collected from the cafeteria at the University of Gujrat, main campus. These samples mainly consisted of fruit and vegetable peels, including potatoes, mangoes, and bananas. After collection, the waste was manually sorted to remove any non-organic contaminants such as paper or plastic. It was then thoroughly washed with distilled water to eliminate any remaining debris. To increase the surface area for efficient drying, larger pieces were manually cut into smaller fragments using a stainless-steel cutter. The prepared pieces were evenly spread on stainless steel trays and left to air-dry for approximately 10 days. During this period, the natural moisture loss reduced the overall water content of the feedstock. The samples were regularly turned over to ensure uniform drying and to prevent microbial growth. Once completely dried, the samples were further processed to achieve a consistent particle size. They were ground using a mechanical grinder and then sieved to obtain uniform particles. The final feedstock was stored in airtight containers to prevent moisture absorption before further experimentation.

Feed Characterization:

In accordance with ASTM guidelines, a proximate analysis of the feedstock from food waste was conducted. Table 1 present the proximate analysis. The test was conducted in a 2 gram. A petri dish containing a feed sample was put in a muffle oven set to 105 ºC, with air for eight hours. It got dry once the moisture content was eliminated. Moisture contents can be computed from the weight difference. The dry feed sample is placed in a muffle furnace at 575 ºC for 25 minutes at air temperature in order to determine the amount of ash present. Five hours later, the weight of the ash was once more measured. The volatile matter was calculated by the ASTM standards. Table 2 present the ultimate analysis.

Following ASTM guidelines, a proximate analysis was conducted on the food waste feedstock. The results are shown in Table 1. The test was performed using a 2-gram sample. A petri dish containing the sample was placed in a muffle oven set at 105°C with airflow for eight hours. The sample was considered dry once all moisture had evaporated. The moisture content was determined by measuring the weight difference before and after drying. To determine the ash content, the dried sample was placed in a muffle furnace at 575°C for 25 minutes in the presence of air. After five hours, the remaining ash was weighed again. The volatile matter was analyzed according to ASTM standards. The results of the ultimate analysis are presented in Table 2.

Table 1. Comparison of proximate Analysis of Food waste with waste residue

Element	**Food waste (wt.%)**	**Corn Cob** [15]	**Sugarcane Bagasse** [8]	**Rice Husk** [16]
Moisture	3.5	12.77	10.4	10.89
Volatile matter	64	2.30	16.4	15.14
Ash Content	6.0	91.16	74.0	73.41
Fixed Carbon	26.5	6.54	13.0	11.44

Table 2. Comparison of Ultimate Analysis of Food waste with waste residue

Element	**Food Waste (wt. %)**	**Corn Cob** [24]	**Sugarcane Bagasse** [23]	**Rice Husk** [25]
Carbon	46	42.10	43.2	41.92
Hydrogen	6.5	5.90	6.70	6.34
Nitrogen	0.48	0.50	0.30	1.85
Sulfur	0.15	0.48	0.20	0.47

The carbon, hydrogen, nitrogen, sulfur, and oxygen contents of the food waste samples were finally determined using an elemental analyzer. First, a precision balance was used to precisely weigh the samples of dried and crushed food waste. After that, a tiny portion of the material was put into the combustion chamber of the analyzer. The material was broken down into gases inside the chamber by burning it at high temperatures while oxygen was present. Carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), and sulfur oxides (SO_x) emitted during burning were all measured by the analyzer. The discovered gases were used to compute the concentrations of carbon, hydrogen, nitrogen, and sulfur. By deducting the total proportion of these elements from 100%, the oxygen content was calculated. The findings gave important details about the food waste's elemental makeup, which made it easier to determine if it was suitable for pyrolysis. Here the food waste analysis is compared with the other residues such as corn, sugarcane and rice. The food waste contains more volatile stuff than rice husk, it promotes improved pyrolysis efficiency and speeds up decomposition. It is advantageous for energy applications because of its high hydrogen content, which improves gas production. Its balanced composition guarantees strong conversion potential even if it contains more ash and moisture than some biomass sources. Food waste provides a competitive yield in pyrolysis products when compared to maize cob and sugarcane bagasse, making it a feasible feedstock for the production of sustainable energy.

The carbon, hydrogen, nitrogen, sulfur, and oxygen content of the food waste samples was determined using an elemental analyzer. First, the dried and crushed food waste samples were accurately weighed using a precision balance. A small portion of the sample was then placed into the analyzer's combustion chamber. Inside the chamber, the material was burned at high temperatures in the presence of oxygen, breaking it down into gases. The analyzer measured the emitted gases, including carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), and sulfur oxides (SO_x). Based on these measurements, the concentrations of carbon, hydrogen, nitrogen, and sulfur were calculated. The oxygen content was determined by subtracting the total percentage of these elements from 100%.

The results provided valuable insights into the elemental composition of food waste, helping assess its suitability for pyrolysis. A comparison was made with other residues such as corn, sugarcane, and rice. Food waste contains more volatile compounds than rice husk, which enhances pyrolysis efficiency and accelerates decomposition. Its high hydrogen content improves gas production, making it beneficial for energy applications. Although food waste has higher ash and moisture content than some biomass sources, its balanced composition ensures strong conversion potential. Compared to maize cobs and sugarcane bagasse, food waste offers a competitive yield in pyrolysis products, making it a viable feedstock for sustainable energy production.

Experimental Methodology:

A lab scale experimental setup is designed to carry out the fast pyrolysis of food waste in the hydrogen atmosphere. The schematic diagram of experimental setup that is shown in Figure 1 consists upon Hydrogen and nitrogen gas cylinders, feeding system, control panel, thermocouples (K type), Pyrolysis reactor and bio-gas collection jar. A lab-scale experimental setup was designed to conduct the fast pyrolysis of food waste in a hydrogen atmosphere. The schematic diagram of the setup, shown in Figure 1, includes hydrogen and nitrogen gas cylinders, a feeding system, a control panel, K-type thermocouples, a pyrolysis reactor, and a biogas collection jar.

The reactor tank's wall is made of stainless steel and can withstand temperatures up to 850 °C, a thickness of 0.2 inches. The tank's head has an inlet for gases and exit for venting gases produced by the pyrolysis reaction, and a 12.5-inch stainless steel capsule where a K type thermocouple can be attached for accurate temperature readings. The thermocouple sensor was positioned so that it would make contact with the reaction zone and provide a reliable reading. Silicon binder and high temperature rubber rings were used to create a completely airtight seal around the entire reactor. The reactor has two condensers, and instead of using a spiral condenser was chosen because it allows for longer contact time between the fumes or vapors and the condensing air, leading to a higher product yield. The experimental work's methodology procedure is illustrated in Figure 2.

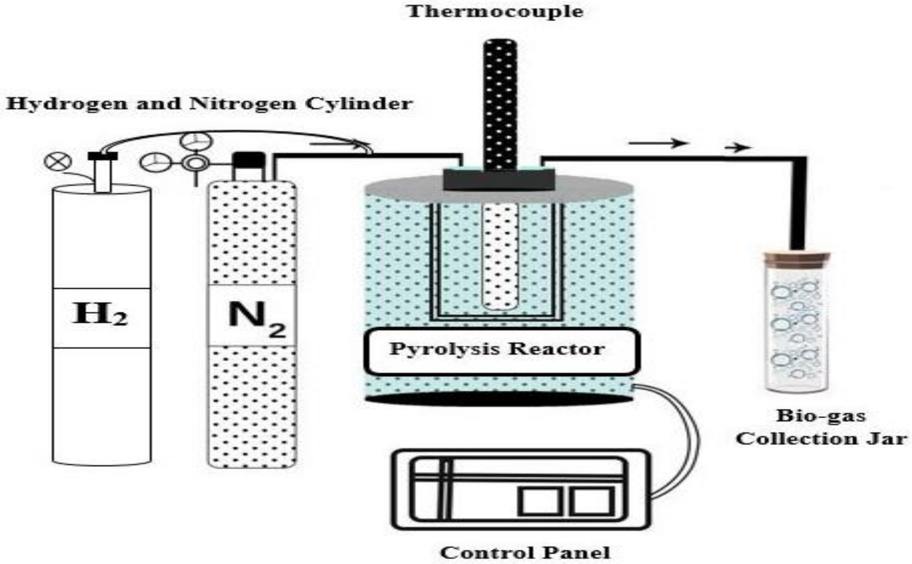

Figure 1. Schematic Diagram of Experimental Setup.

The reactor tank is made of stainless steel with a 0.2-inch thickness and can withstand temperatures up to 850 °C. The tank's head includes an inlet for gas entry, an outlet for venting gases produced during pyrolysis, and a 12.5-inch stainless steel capsule where a K-type thermocouple is attached for precise temperature measurement. The thermocouple sensor is positioned to ensure direct contact with the reaction zone for accurate readings. To maintain an airtight seal, the reactor is secured with a silicon binder and high-temperature rubber rings. It is equipped with two condensers, and a spiral condenser was chosen instead of a standard one, as it increases the contact time between vapors and the cooling air, improving product yield. The methodology for the experimental procedure is illustrated in Figure 2.

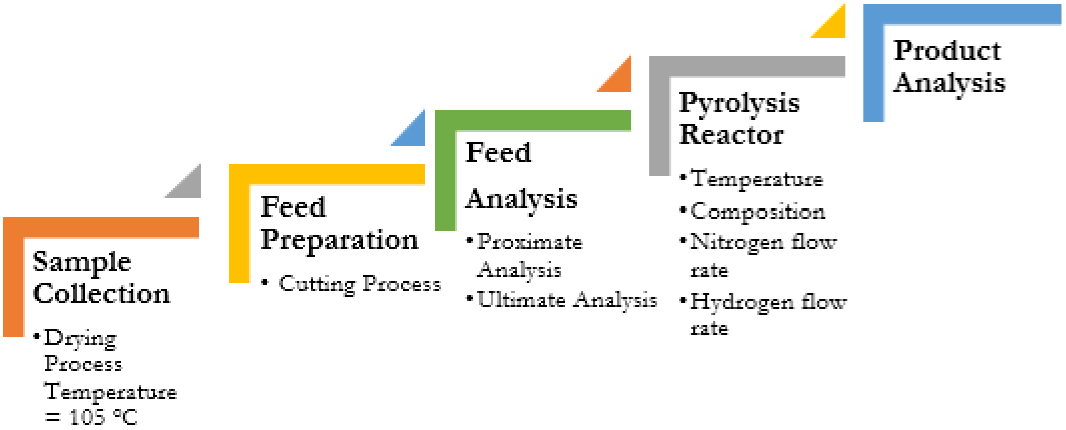

Figure. 2 Flow Diagram of Methodology

At first,15 gram. sample was taken and placed in the reactor's sample cup then the reactor's body was sealed with a silicon ring to prevent the fumes from escaping. The reactor's second outlet is piped to the condenser portion, where vapors are removed by spiral condensers and the inlet is connected to a gases cylinders. The residence time for all the experiments is kept 2 sec. As the process starts, char produced remains on the mesh inside the reactor, the condensable vapors of bio-oil are collected in the collection system after condensation and the non-condensable gases are collected in the gas balloons.

First, a15gram sample was placed in the reactor's sample cup, and the reactor was sealed with a silicon ring to prevent fumes from escaping. The second outlet of the reactor was connected to the condenser section, where vapors were condensed using spiral condensers, while the inlet was linked to gas cylinders. The residence time for all experiments was maintained at 2 seconds. During the process, the produced char remained on the mesh inside the reactor. The condensable vapors of bio-oil were collected in the collection system after condensation, while the non-condensable gases were stored in gas balloons.

Results:

Experimental Run:

The pyrolysis experiments were conducted using a fixed-bed reactor to investigate the influence of operating temperature and gas composition on product distribution. In order to guarantee consistent thermal decomposition of the food waste residue, the reactor was externally heated to target temperatures between 600 °C and 800 °C. The heating rates were precisely controlled. Before every experiment, the system was nitrogen-purged to remove any remaining gases. A range of gas compositions, including a pure nitrogen atmosphere and nitrogen-hydrogen mixes with hydrogen levels of 10% and 20% by volume, were used to pyrolysis the feedstock. The total gas flow rate was adjusted to either 100, 90, or 80 ml/min, ensuring a consistent residence time for the volatiles within the reactor. The bio-char was gathered and weighed at the end of each run, and the bio-oil portion was condensed and measured. Mass balance was used to determine the remaining bio-gas fraction. A thorough analysis of the impact of temperature on the yield distribution of bio-oil, bio-char, and bio-gas showed notable differences in product composition across experimental settings. The effects of adding hydrogen to the pyrolysis environment on secondary processes, thermal cracking, and total product selectivity were also evaluated.

The pyrolysis experiments were carried out using a fixed-bed reactor to study how temperature and gas composition affect product distribution. To ensure uniform thermal decomposition of the food waste residue, the reactor was externally heated to temperatures between 600 °C and 800 °C, with precise control over heating rates. Before each experiment, the system was purged with nitrogen to remove any residual gases.

The feedstock was pyrolyzed under different gas compositions, including a pure nitrogen atmosphere and nitrogen-hydrogen mixtures with hydrogen concentrations of 10% and 20% by volume. The total gas flow rate was set at 100, 90, or 80 ml/min to maintain a consistent residence time for volatile compounds in the reactor. At the end of each experiment, the bio-char was collected and weighed, while the bio-oil fraction was condensed and measured. The remaining bio-gas fraction was determined using mass balance calculations. A detailed analysis of temperature effects on the yields of bio-oil, bio-char, and bio-gas revealed significant variations in product composition under different conditions. Additionally, the impact of hydrogen on secondary reactions, thermal cracking, and overall product selectivity was evaluated.

Table 3 shows the effect of operating parameter (temperature) on the products yield in the presence of only nitrogen. The maximum yield of bio-oil comes on 600 ºC after that its yield decreases. As the temperature increases from 600 ºC to 800 ºC, the gaseous product yield increases from 17.65 wt. % to 45.68 wt. %. Due to increase in temperature, more thermal degradation takes places and gaseous product yield increases. Table 3 shows the results of product yields in the presence of hydrogen gas (10 % and 20 %). The gas product yield increases till 45.68 wt. % under the effect of 10 % hydrogen but decreases to 40.58 wt. % when 20 % hydrogen is supplied.

Table 3. Product Yield of Pyrolysis of food waste residue under composition of Nitrogen and Hydrogen flow, at different Temperature

Test Run	Reactor Temperature (°C)	N_2 Flow Rate (mL/min)	Hydrogen Content (Vol %)	Bio oil (wt. %)	Bio-Char (wt. %)	Bio-Gas (wt. %)
Run # 01	600	100	0%	57.1± 14.04	25.25± 6.91	17.65± 8.97
Run # 02	650	100	0%	52.78± 14.04	22.95± 6.91	24.27± 8.97
Run # 03	700	100	0 %	47.9± 14.04	20.3± 6.91	31.8± 8.97
Run # 04	750	100	0 %	45.6± 14.04	17.5± 6.91	38.9± 8.97
Run # 05	800	100	0 %	40.8± 14.04	15± 6.91	36.5± 8.97
Run # 06	600	90	10 %	49.88± 14.04	29.45± 6.91	20.67± 8.97
Run # 07	650	90	10 %	38.65± 14.04	33.68± 6.91	27.60± 8.97
Run # 08	700	90	10 %	30.15± 14.04	31.87± 6.91	37.98± 8.97
Run # 09	750	90	10 %	22.89± 14.04	31.42± 6.91	45.68± 8.97
Run # 10	800	90	10 %	14.7± 14.04	30.88± 6.91	41.43± 8.97
Run # 11	600	80	20 %	47.95± 14.04	32.7± 6.91	19.35± 8.97
Run # 12	650	80	20 %	36.89± 14.04	37.3± 6.91	25.81± 8.97
Run # 13	700	80	20 %	29.1± 14.04	34.65± 6.91	36.25± 8.97
Run # 14	750	80	20 %	21.65± 14.04	34.56± 6.91	40.58± 8.97
Run # 15	800	80	20 %	13.1± 14.04	34.38± 6.91	38.72± 8.97

Table 3 presents the effect of operating temperature on product yield in a nitrogen-only environment. The highest bio-oil yield is achieved at 600 °C, after which it starts to decline. As the temperature increases from 600 °C to 800 °C, the gaseous product yield rises from 17.65 wt.% to 45.68 wt.% due to enhanced thermal degradation. Table 3 also shows the product yields in the presence of hydrogen gas (10% and 20%). With 10% hydrogen, the gaseous product yield reaches a maximum of 45.68 wt.%. However, when the hydrogen concentration increases to 20%, the yield decreases to 40.58 wt.%.

Pyrolysis product yield:

Based on the mass distribution of the solid, liquid, and gaseous fractions produced by the rapid pyrolysis of food waste in the presence of hydrogen, the yield of pyrolysis products was calculated. The findings showed that the operating temperature had a major impact on the product dispersion. At an ideal temperature of 750°C, the pyrolysis process produced 22.89% biochar, 31.42% bio-oil, and 45.68% gaseous products. The yield of pyrolysis products was determined based on the mass distribution of solid, liquid, and gaseous fractions generated during the rapid pyrolysis of food waste in a hydrogen environment. The results indicated that operating temperature significantly influenced product distribution. At an optimal temperature of 750°C, the process yielded 22.89% biochar, 31.42% bio-oil, and 45.68% gaseous products.

Effect of Operating Parameters on Bio-gas yield %:

Operating parameters such as temperature, feedstock composition, and gas environment (H_2, N_2) all had a substantial impact on the production and composition of biogas generated by fast pyrolysis of food waste in the presence of hydrogen [20]. A larger gas yield, especially methane (CH_4) and hydrogen (H_2), was obtained by increasing the temperature, which boosted thermal cracking reactions. The ideal range was found at 750 °C. Beyond this range, excessive cracking decreased the gas's calorific value by increasing the formation of carbon monoxide (CO) and carbon dioxide (CO_2). Operating factors such as temperature, feedstock composition, and gas environment (H_2, N_2) significantly influenced biogas production and composition during the fast pyrolysis of food waste in a hydrogen atmosphere [20]. Higher temperatures enhanced thermal cracking reactions, leading to increased gas yield, particularly methane (CH_4) and hydrogen (H_2). The optimal temperature was found to be 750°C. Beyond this point, excessive cracking reduced the gas's calorific value by increasing the formation of carbon monoxide (CO) and carbon dioxide (CO_2).

Effect of Composition:

Figure 3 illustrates how the yield percentage changes with varying composition ratios (100:00, 90:10, and 80:20) under five different temperatures: 600 °C, 650 °C, 700 °C, 750 °C, and 800 °C. A clear upward trend is observed with increasing temperatures, indicating that higher temperatures result in higher yields across all composition ratios. In conclusion, the results demonstrate that both temperature and composition ratio are crucial factors in maximizing yield. A composition ratio of Nitrogen and Hydrogen of 90:10 combined with a temperature of 750 °C offers the most efficient outcome. This harmonious interplay between temperature and composition highlights the potential for refining industrial processes to enhance yield performance.

Figure 3 shows how yield percentage varies with different composition ratios (100:00, 90:10, and 80:20) at five temperatures: 600 °C, 650 °C, 700 °C, 750 °C, and 800 °C. The results indicate a clear upward trend, where higher temperatures lead to increased yields across all composition ratios. Overall, the findings highlight that both temperature and composition ratio play a crucial role in maximizing yield. The most efficient outcome is achieved with a nitrogen-to-hydrogen ratio of 90:10 at 750 °C. This balance between temperature and composition underscores the potential for optimizing industrial processes to improve yield performance.

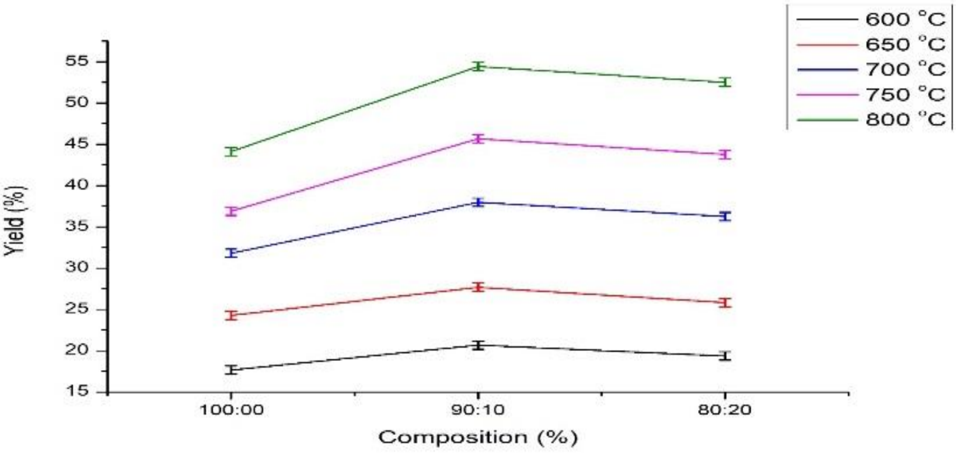

Figure 3. Effect of different composition of H_2 and N_2 in the Yield

Effect of Temperature:

Figure 4 presents the relationship between temperature and yield (wt. %) for three different flow rates: 100 ml/min, 90 ml/min, and 80 ml/min. The trend reveals that as the temperature increases from 600 °C to 700 °C, the yield significantly improves across all flow rates, indicating that higher temperatures enhance the reaction efficiency. However, beyond 700 °C, a decrease in yield is observed, which may suggest thermal degradation or the onset of unfavorable side reactions. The highest yield is achieved at 700 °C for all flow rates, with the 90 ml/min condition (red line) exhibiting the maximum performance.

Figure 4 illustrates the relationship between temperature and yield (wt.%) for three different flow rates: 100 ml/min, 90 ml/min, and 80 ml/min. The results show that increasing the temperature from 600 °C to 700 °C significantly enhances yield across all flow rates, indicating improved reaction efficiency. However, beyond 700 °C, the yield starts to decline, likely due to thermal degradation or unwanted side reactions. The highest yield is observed at 700 °C for all flow rates, with the 90 ml/min condition (red line) showing the best performance.

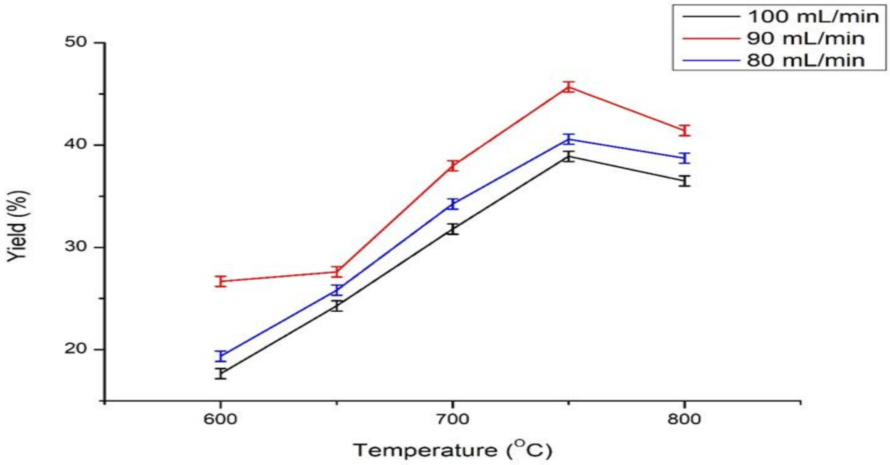

Figure 4. Effect of pyrolysis temperature in the Yield

Effect of Hydrogen Percentage:

Figure 5 illustrates the relationship between hydrogen flow rate (%) and yield (%) at varying temperatures: 600 °C, 650 °C, 700 °C, 750 °C, and 800 °C. The results reveal distinct trends at each temperature, with yield increasing as the hydrogen flow rate rises from 0 % to 10 %, followed by a decline at 20 %. The observed peak at 10 % indicates an optimal hydrogen flow rate for maximizing yield. At lower temperatures, such as 600 °C and 650 °C, the yield remains relatively low compared to higher temperatures, suggesting that the reaction is less efficient under these conditions. However, as temperature increases to 700 °C, 750 °C, and 800 °C, the yield significantly improves. The highest yield is observed at 750 °C, particularly at the optimal hydrogen flow of 10 %, as indicated by the magenta curve. Beyond 750 °C, the yield slightly decreases, possibly due to competing reactions or thermal instability.

Figure 5 shows the relationship between hydrogen flow rate (%) and yield (%) at different temperatures: 600 °C, 650 °C, 700 °C, 750 °C, and 800 °C. The results indicate a clear trend—yield increases as the hydrogen flow rate rises from 0 % to 10 %, then declines at 20 %. This peak at 10 % suggests an optimal hydrogen flow rate for maximizing yield. At lower temperatures (600 °C and 650 °C), the yield remains relatively low, indicating lower reaction efficiency. However, as the temperature increases to 700 °C, 750 °C, and 800 °C, the yield improves significantly. The highest yield is recorded at 750 °C, particularly at the 10% hydrogen flow rate, as shown by the magenta curve. Beyond 750 °C, the yield slightly decreases, likely due to competing reactions or thermal instability.

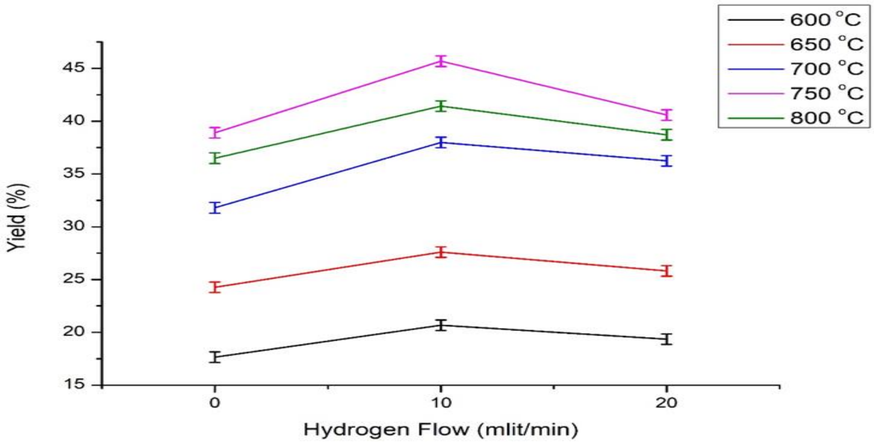

Figure 5. Effect of hydrogen composition in the Yield

Discussion:

The results of the study demonstrate that pyrolyzing food waste with hydrogen results in a significantly greater output of gaseous products, specifically methane (CH_4) and hydrogen (H_2). At 90:10 nitrogen-to-hydrogen ratio at 750 °C, the maximum gas output of 45.68 wt.% was attained. The increase of temperature during fast pyrolysis process not only increase the gaseous product yield but also increases the composition of hydrogen, methane, carbon mono oxide and ethane. The presence of hydrogen facilitates the breaking down the bonding of different heavy molecules. The free radical mechanism reaction rate increases at high temperatures and the composition of CO, H_2 and CH_4 increases but at the same stage the percentage of carbon dioxide, ethane and propene decrease [10].

While the creation of bio-oil and gaseous products was promoted by an increase in temperature, the production of biochar was comparatively higher at lower temperatures. Methane (CH_4), hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2) made up the majority of the gaseous component, which showed a rising trend at higher temperatures, indicating enhanced thermal cracking and secondary reactions [17].

By raising the concentration of hydrocarbons like methane, the presence of hydrogen in the reaction environment enhanced the gas yield and quality [19]. According to the findings, hydrogen-assisted pyrolysis is a viable method for environmentally friendly waste-to-energy applications since it improves the conversion of food waste into useful energy products [14].

Food waste's composition also mattered; fractions high in protein and cellulose contributed more to the generation of gas, whilst components rich in lipids and carbohydrates promoted the development of bio-oil. By encouraging hydrocracking reactions, raising methane yield, and decreasing tar formation, the addition of hydrogen greatly enhanced the quality of biogas. In contrast, nitrogen, as an inert carrier gas, changed heat transfer and volatile residence time but did not actively participate in reactions [21] [22]. A lower methane yield and a larger production of CO_2 were noted when nitrogen was substituted for hydrogen, underscoring the crucial role that hydrogen plays in improving gas quality [23]. In hydrogen- assisted pyrolysis, our results highlight the significance of controlling operating conditions to maximize biogas yield and energy efficiency [24].

The composition of food waste plays a crucial role in determining the distribution of pyrolysis products, including bio-oil, bio-char, and biogas. The three major organic components—cellulose, lipids, and proteins—undergo different thermal decomposition pathways, influencing the yield and composition of the final products. Cellulose, a major structural component of plant-based food waste, primarily decomposes into volatile gases, tars, and some residual char. Its thermal degradation occurs between 280–400 °C, favoring bio-oil production at lower temperatures, but at higher temperatures (>700°C), secondary cracking enhances gas yield, particularly CO, CO_2, and H_2. The presence of hydrogen facilitates further gasification of cellulose-derived compounds, improving the yield of hydrogen and methane-rich gases. In food waste rich in cellulose (e.g., vegetable peels, rice husk), the thermal degradation trends indicate that higher pyrolysis temperatures combined with hydrogen enhance gaseous product formation, aligning with the observed peak gas yield at 750 °C in this study.

In contrast, lipids (fats and oils) decompose at lower temperatures (300–500 °C) and contribute significantly to bio-oil production. However, as the temperature increases, thermal cracking of lipids leads to higher gas yields, producing alkanes, alkenes, CH_4, and CO_2. The presence of hydrogen promotes hydrocracking, which breaks down heavier hydrocarbons into lighter gaseous products like methane and ethane. This explains why hydrogen-assisted pyrolysis enhances methane production at 750 °C, particularly in food waste with high lipid content such as dairy products, cooking oils, and meat fats. However, when hydrogen concentration is increased to 20 %, excessive hydrogenation can lead to lower gas yield, as seen in the experimental results, due to the inhibition of further volatile formation.

The study results show that pyrolyzing food waste in a hydrogen atmosphere significantly increases the yield of gaseous products, particularly methane (CH_4) and hydrogen (H_2). The highest gas yield of 45.68 wt.% was achieved at a nitrogen-to-hydrogen ratio of 90:10 at 750 °C. Higher temperatures in fast pyrolysis not only boost gas production but also enhance the composition of hydrogen, methane, carbon monoxide, and ethane. Hydrogen helps break down heavy molecular bonds, accelerating free radical reactions at high temperatures. This leads to increased CO, H_2, and CH_4 formation while reducing CO_2, ethane, and propene content.

While higher temperatures promoted bio-oil and gas production, biochar yield remained higher at lower temperatures. The main gaseous products—methane (CH_4), hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2)—showed a rising trend at elevated temperatures, indicating increased thermal cracking and secondary reactions. The presence of hydrogen improved gas yield and quality by raising hydrocarbon concentrations, especially methane. These findings highlight hydrogen-assisted pyrolysis as a promising waste-to-energy method for efficiently converting food waste into valuable energy products.

The composition of food waste also played a key role. Protein- and cellulose-rich fractions contributed more to gas production, while lipid- and carbohydrate-rich components favored bio-oil formation. Hydrogen enhanced hydrocracking, increased methane yield, and reduced tar formation. In contrast, nitrogen, acting as an inert carrier gas, influenced heat transfer and volatile residence time without actively participating in reactions. Replacing hydrogen with nitrogen led to lower methane yields and higher CO_2 production, emphasizing hydrogen's crucial role in improving gas quality. Controlling operating conditions in hydrogen-assisted pyrolysis is essential for optimizing biogas yield and energy efficiency.

Food waste composition directly affects the distribution of pyrolysis products, including bio-oil, biochar, and biogas. The three primary organic components—cellulose, lipids, and proteins—follow different thermal decomposition pathways, influencing the final product yield and composition. Cellulose, a key structural component of plant-based food waste, primarily degrades into volatile gases, tars, and residual char. It decomposes between 280–400°C, favoring bio-oil production at lower temperatures. However, at temperatures above 700 °C, secondary cracking increases gas yield, particularly CO, CO_2, and H_2. The presence of hydrogen enhances the gasification of cellulose-derived compounds, improving hydrogen- and methane-rich gas production. In cellulose-rich food waste (e.g., vegetable peels, rice husks), higher pyrolysis temperatures combined with hydrogen favor gas formation, aligning with the peak gas yield observed at 750 °C.

Lipids (fats and oils) break down at lower temperatures (300–500 °C), mainly contributing to bio-oil formation. However, as the temperature rises, lipid thermal cracking increases gas production, generating alkanes, alkenes, CH_4, and CO_2. Hydrogen promotes hydrocracking, breaking down heavier hydrocarbons into lighter gases like methane and ethane. This explains why hydrogen-assisted pyrolysis enhances methane production at 750 °C, especially in food waste with high lipid content, such as dairy products, cooking oils, and meat fats. However, at 20% hydrogen concentration, excessive hydrogenation can reduce gas yield by inhibiting further volatile formation, as observed in the experimental results.

Proteins, found in significant amounts in food waste sources like meat, legumes, and eggs, decompose at 250–600 °C, forming char, ammonia (NH_3), hydrogen cyanide (HCN), and nitrogen-containing bio-oil compounds. Unlike cellulose and lipids, proteins contribute more to char formation, especially at lower temperatures, due to their complex nitrogenous structures. However, at high temperatures (>700 °C), proteins undergo secondary decomposition, releasing H_2 and CO_2. The introduction of hydrogen in the reaction environment further enhances H_2 production while reducing nitrogenous impurities like NH_3 and HCN, which would otherwise degrade gas quality. This suggests that the increase in hydrogen concentration (10%) optimizes biogas composition, but an excessive hydrogen supply (20%) may limit the thermal degradation of protein-rich feedstocks, reducing the overall gas yield.

Proteins, abundant in food waste sources such as meat, legumes, and eggs, break down at temperatures between 250–600°C, producing char, ammonia (NH_3), hydrogen cyanide (HCN), and nitrogen-containing bio-oil compounds. Unlike cellulose and lipids, proteins generate more char, especially at lower temperatures, due to their complex nitrogenous structures. However, at temperatures above 700 °C, proteins undergo secondary decomposition, releasing H_2 and CO_2. Introducing hydrogen into the reaction environment further boosts H_2 production while reducing nitrogenous impurities like NH_3 and HCN, which can lower gas quality. This indicates that a 10% hydrogen concentration optimizes biogas composition, but an excessive supply (20%) may hinder the thermal breakdown of protein-rich feedstocks, reducing overall gas yield.

Conclusion:

A fast pyrolysis on Food waste residue was carried out using a fixed bed reactor operating at atmospheric pressure. The Investigation showed that the optimum pyrolysis temperature for obtaining the maximum bio-gas yield at 750 °C. The findings of this investigation indicate that 750 °C. Is the optimum temperature. With a nitrogen to hydrogen ratio of 90:10, a maximum biogas output of 45.68 weight percent is achieved. Bio-gas yields were increased by raising the pyrolysis temperature while keeping the ratio constant. When 90 % nitrogen and 10 % hydrogen were used at 750 °C, the maximum gaseous product yield is obtained. Hydrogen aided in hydrocracking reactions, which decreased the synthesis of tar and heavy hydrocarbons while increasing the production of valuable gases including hydrogen (H_2) and methane (CH_4). The technique became more appropriate for clean energy applications as a result of the enhanced hydrogen-to-carbon ratio and the more energy-dense syngas composition. Temperature differences also had a noticeable impact on the distribution of the product; higher temperatures encouraged the conversion of solid and liquid fractions into non-condensable gases, while lower temperatures favored the creation of biochar because of incomplete thermal decomposition. Hydrogen-assisted pyrolysis is a potential method for managing food waste sustainably and producing renewable energy as these studies offer important insights into how to optimize it for increased syngas production. Process efficiency can be greatly increased, resulting in larger energy yields and a smaller environmental effect, by carefully regulating the temperature and gas composition. Furthermore, the potential for industrial-scale applications particularly in waste-to-energy conversion technologies is highlighted by the ability to precisely control product distribution through exact operating conditions. Future research will involve the development and optimization of bio-based catalysts for the production of high-quality and cost-efficient bio-gas.

A fast pyrolysis process was conducted on food waste residue using a fixed-bed reactor at atmospheric pressure. The investigation revealed that 750 °C is the optimal pyrolysis temperature for achieving the highest biogas yield. With a nitrogen-to-hydrogen ratio of 90:10, a maximum biogas output of 45.68 wt.% was obtained. Increasing the pyrolysis temperature while maintaining this ratio further enhanced biogas yields. At 750 °C, with 90% nitrogen and 10% hydrogen, the highest gaseous product yield was achieved. Hydrogen played a key role in hydrocracking reactions, reducing tar and heavy hydrocarbon formation while boosting the production of valuable gases such as hydrogen (H_2) and methane (CH_4). This improved the hydrogen-to-carbon ratio, resulting in a more energy-dense syngas composition, making the process more suitable for clean energy applications.

Temperature variations also significantly influenced product distribution. Higher temperatures promoted the conversion of solid and liquid fractions into non-condensable gases, whereas lower temperatures favored biochar formation due to incomplete thermal decomposition. These findings highlight hydrogen-assisted pyrolysis as a promising method for sustainable food waste management and renewable energy production. By carefully controlling temperature and gas composition, process efficiency can be significantly improved, leading to higher energy yields and a reduced environmental footprint. Moreover, the ability to fine-tune operating conditions for precise product distribution enhances the potential for industrial-scale applications, particularly in waste-to-energy technologies. Future research will focus on developing and optimizing bio-based catalysts to produce high-quality, cost-effective biogas.

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