

Article

Combustion of Date Stone and Jojoba Solid Waste in a Hybrid Rocket-like Combustion Chamber

Saleh B. Alsaidi ¹, Jeongmoo Huh ^{1,2,*}  and Mohamed Y. E. Selim ^{1,3,*} 

¹ Department of Mechanical and Aerospace Engineering, College of Engineering, United Arab Emirates University, Al Ain P.O. Box 15551, Abu Dhabi, United Arab Emirates; 201970152@uaeu.ac.ae

² National Space Science and Technology Center (NSSTC), United Arab Emirates University, Al Ain P.O. Box 15551, Abu Dhabi, United Arab Emirates

³ National Water and Energy Center (NWECC), United Arab Emirates University, Al Ain P.O. Box 15551, Abu Dhabi, United Arab Emirates

* Correspondence: j.huh@uaeu.ac.ae (J.H.); mohamed.selim@uaeu.ac.ae (M.Y.E.S.)

Abstract: The performance of two solid biomass wastes, date stone and jojoba solid waste, was experimentally examined for their potential application in combustion and propulsion systems. The fuels were tested in a hybrid rocket-like combustion environment, and the test result was analyzed with combustion and propulsion parameters. The performance of both fuels was comparatively evaluated and compared with a conventional hydrocarbon fuel in a hybrid rocket, with paraffin wax serving as a baseline. A compression device was introduced to compress the solid biomass wastes into a circular-shaped fuel grain compatible with a hybrid rocket combustion chamber with a hot surface ignitor. Thermogravimetric analysis (TGA) and chemical equilibrium analysis (CEA) results revealed that the performance of the biomass fuel can be comparable to conventionally used hydrocarbon paraffin-wax-based propellant within a certain range of oxidizer-to-fuel ratio, in terms of theoretical specific impulse performance. Through experimental performance tests, it was found that the compressed biomass fuel grains were successfully ignited and produced thrust. Both biomass fuels tested in a hybrid rocket combustion chamber are expected to pave the way for further developments in biomass fuels in the waste-to-energy field for their application in combustion and propulsion systems, potentially replacing fossil fuels with renewable resources.

Keywords: biomass fuel; waste-to-energy; combustion; propulsion; hybrid rocket; date stone; jojoba



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1. Introduction

The world is moving forward to replace fossil fuels and hydrocarbons with green alternatives in all fields, e.g., in power generation, transportation, and rocket propulsion. The propellants used in almost all current rocket-based applications, like military or space programs, have an impact on the environment at different levels. Hydrazine (N₂H₄), for example, is a highly toxic and carcinogenic liquid fuel that can be used for monopropellant as well as bipropellant systems. Unsymmetrical dimethylhydrazine (UDMH) is another toxic and carcinogenic liquid fuel used in hypergolic propellant rocket systems. Nitrogen tetroxide (N₂O₄) is a highly corrosive and toxic oxidizer commonly used in hypergolic propellant combinations with various fuels. Accidental releases of these fuels can pose risks in terms of environmental contamination and health hazards. While kerosene is generally considered less toxic than other rocket propellants, if mishandled, it can potentially lead to environmental contamination of soil and groundwater, with adverse effects on the local ecosystem in the event of a spill or leakage. Furthermore, with hydrocarbon fuels, a considerable part of the gaseous exhaust contributes to the increase in CO₂ levels in the atmosphere [1]. In addition to ecofriendliness, the economic operation of combustion and propulsion systems is a key aspect of the so-called new space era.

In many combustion applications, researchers have presented many alternatives including biomass-based substances. Date stone is one of these biomass-based substances and is the largest unutilized bioresource in the Middle East, North Africa, and the United Arab Emirates (UAE). The UAE has 7% of the world's date palm trees, is one of the top producers of dates, and has one of the greatest untapped reserves of date stone in the Middle East and North Africa [2]. The seed represents a third of the total weight of the date and is an unutilized potential energy source that could also be converted into a valuable chemical feedstock [3]. Many studies have been conducted to investigate the potential use of date stones in various applications using different methodologies such as oil extraction, posterior biodiesel production, thermal pyrolysis, and replacing coal in furnace combustion.

Jojoba, also known as *Sommondisa Chinensis*, is a shrub that grows all over the world, although it is particularly common in the deserts of northern Mexico, southern America, and some regions of the Middle East and North Africa. Due to its high oil content of approximately 50%, it became widely used in the pharmaceutical industry, cosmetics, floor waxes, and many more applications [4,5]. Jojoba oil has a high energy content of approximately 42.4 MJ/kg, which makes it comparable to diesel fuel [6]. Furthermore, it releases a negligible amount of SO_x and NO_x. In recent years, most of the studies on jojoba focused on using jojoba oil as a potential biofuel, either as pure oil or in blends in diesel compression-ignition engines [7–13]. After oil extraction, the solid jojoba waste can be collected and milled into a fine powder with the potential to be used as a renewable resource. However, only a few studies have been conducted to investigate the combustion characteristics of jojoba solid waste.

For date stone biowaste fuel, there were several documented efforts to calculate the heating value of date stone. Elnajjar et al. [14] measured the heating value of date stone using a bomb calorimeter before and after liquid oil extraction, and they discovered that it ranged from 28.55 MJ/kg (before liquid oil was removed) to 29.63 MJ/kg (after liquid oil was extracted). A combustion investigation of date palm stones in a laboratory-scale furnace was carried out by Al-Widyan and Al-Muhtaseb [15] and Wisniak [16] in an attempt to examine the physical and thermal characteristics of the date stones. Al-Omari [17] examined coal under the same conditions with the intention of comparing it with date stones, whereas Elmay et al. [18] compared date stones with other palm tree waste. Many variables were examined, including ash, moisture (M), fixed carbon (FC), and volatile matter (VM), which is the flammable material left over after the product is heated and the VM has emanated. Table 1 summarizes some of the results from the two studies for date stones compared with coal. In a furnace, date stones demonstrated faster combustion and heat transfer rates than coal due to their increased volatile matter and lower ash content. In terms of cost and emission, date stone is expected to reduce coal costs by up to 40% while limiting emissions of SO_x and NO_x, which will have a positive impact on the environment and public health [19]. Understanding the combustion characteristics of date stones requires knowledge of the chemical composition and metal content. Table 2 compares the results of the two previous studies that investigated the chemical composition of date stones in terms of carbon (C), nitrogen (N), oxygen (O), and oxygen/carbon ratio (O/C). Variation in content percentages of the chemical elements in the date stones was expected due to the different types of date palms and the regions in which they were produced.

Many studies have been conducted investigating the feasibility of converting date stones to activated carbon for chemical characterization or purification needs using thermogravimetric analysis techniques [3,6,16,19–21]. However, there have been limited reports on the practical application of biomass fuels for application in combustion and propulsion. Thus, it was required to conduct an experimental analysis of combustion characteristics using a ground test setup for a propulsion system as well as a thermogravimetric analyzer (TGA), as has been done in this study. For these experiments, date stone flakes were prepared as shown in Figure 1a, and jojoba solid waste, the remaining flakes after applying the oil extraction process to jojoba fruit, as shown in Figure 1b. Similar to date stone, the chemical composition data of jojoba waste were required to estimate and understand

the combustion performance. Analyzed chemical composition data from two previous studies focusing on the presence of specific atoms, such as carbon (C), nitrogen (N), oxygen (O), and ash, are shown in Table 3. Selim et al. [11] investigated the combustion performance of jojoba solid waste in a furnace application and noted that high gasification rates were observed as a result of a high volatile matter of 76% and a low moisture content of 4%. Moreover, high combustion and heat transfer could be achieved with a sufficient amount of air.

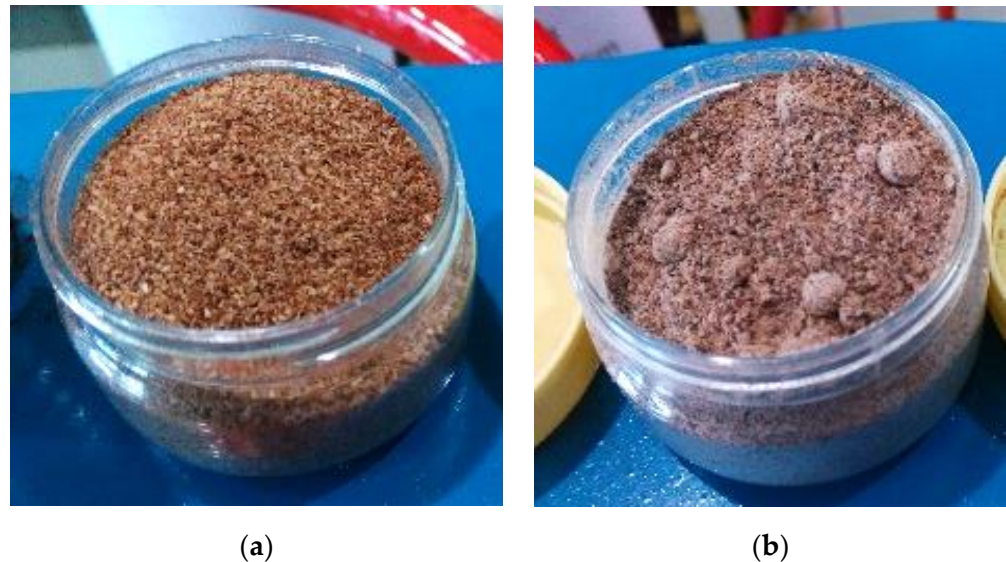


Figure 1. Date stones solid waste sample (a) and jojoba solid waste sample (b).

A conventionally used fuel grain, such as paraffin, can be considered for comparative performance analysis for the biowaste fuel grains. Paraffin was first investigated as a potential propellant in the 1950s [12] and has been continuously studied for the reinforcement of fuel formulation, for implementing a variety of additives to improve combustion performance, and for researching the ballistic effects of the fuel's entrainment [3,22] despite its brittle behavior, in contrast to most common hydrocarbon fuels. Paraffin's inability to prevent structural damage during grain manufacture, handling, casting, and transformation is a result of its inadequate mechanical strength. In practical applications, the mechanical characteristics of paraffin-based propellant are typically altered by mixing it with thermoplastic polymers [23,24] or by adding additives to prevent internal and surface rips and microcracks that may impact the fuel's combustion performance. In addition, as the high paraffin-wax regression rate is a result of paraffin droplets being drawn into the flame by evaporated paraffin, with possibly unburned vaporized droplets discovered by Kim et al. [23], it was recommended that this issue can be resolved by using a tiny quantity of polymeric binder to retard the release of paraffin droplets [24]. To enhance its mechanical properties and decrease its fragility, the paraffin was combined with satiric acid (octadecanoic acid) and carbon nanopowder before the firing tests carried out in this study. Table 4 lists typical paraffin-wax thermal characteristics, such as melting point, density (ρ), and molecular weight (MW), in comparison to those of polyethylene.

In this study, the solid waste from date stone and jojoba was employed as a solid fuel for a hybrid rocket and comparatively evaluated with paraffin fuel. Fuel grains were manufactured in a way that they were compatible with a hybrid rocket combustion chamber. Firing tests were conducted to determine the performance of the biowaste fuels from a combustion and propulsion point of view.

Table 1. Physical characteristics of date stones and coal.

Study (Fuel)	M (%)	VM (%)	FC (%)	Ash (%)
Elmay et al. [18] (date stones)	6.4	74.1	17.5	1.2
S.-A.B. Al-Omari [17] (date stones)	7	69	23	1.0
S.-A.B. Al-Omari [17] (coal)	5	12	73	10

Table 2. Chemical composition of date stones.

Attempt	C (%)	N (%)	O (%)	O/C
Sait et al. [25]	45.30	1.00	47.20	1.04
E. Elnajjar et al. [14]	46.26	12.45	37.91	0.82
S.-A.B. Al-Omari [20]	48.39	0.78	N/A	N/A

Table 3. Chemical composition of jojoba solid waste.

Reference	C (%)	H (%)	N (%)	O (%)	Ash (%)
Al-Widyan et al. [15]	52.91	7.71	2.18	22.5	14.7
Selim et al. [11]	49.63	8.41	3.24	19.6	N/A

Table 4. Characteristics of propellants [26].

Propellant	Melting Point °C	Density Kg/m ³	Molecular Weight g/mol
Paraffin wax	59–66	920	394
Polyethylene	104	918	96,000

2. Theoretical Performance Estimation and Experimental Test Setup

2.1. Fuel Properties Analysis and Expected Performance

Prior to experimental performance testing, a preliminary analysis of the thermal properties of the biomass propellants was conducted utilizing a thermo-gravimetric analyzer (TGA). Mettler Toledo TGA2 Thermogravimetric Analyzer manufactured in the US was utilized for the investigation of the samples in the temperature range from 25 °C to 900 °C in a nitrogen (N₂) atmosphere, and the pre-set heating rate was 10 °C/min. The samples were initially put into the furnace chamber with a mass of 10.5 mg. The TGA test results are provided in Figure 2 for the weight loss derivative (as a derivative thermogravimetric (DTG) curve) and in Figure 3 for the weight loss percentage with regard to temperature. Despite the possible differences in properties depending on the environments where the biomass was produced, the TGA results obtained were similar to other studies [19,20,25,27] in that they revealed a significant weight loss after 200 °C. The date stone material had the maximum weight loss rate when heated to 302 °C, whereas the jojoba had the maximum weight loss rate when heated to 344 °C. The temperature range for the maximum reaction rate and energy conversion was between 150 °C and 500 °C for both date stone and jojoba biomass fuel. The results demonstrated that date stone can transform into a volatile compound more quickly, indicating the different burning characteristics of the two fuels. Similar patterns emerged for both fuels from the beginning until they reached 900 °C, as shown in Figure 2. When the temperature reached 900 °C, the decomposition of date stone was higher (89%) than that of jojoba (79%). In addition, the amount of ash that was left at the end of the test was 6.4% for the date stone, which was smaller compared to 20.7% with the jojoba sample, demonstrating that the date stone was more completely decomposed than jojoba.

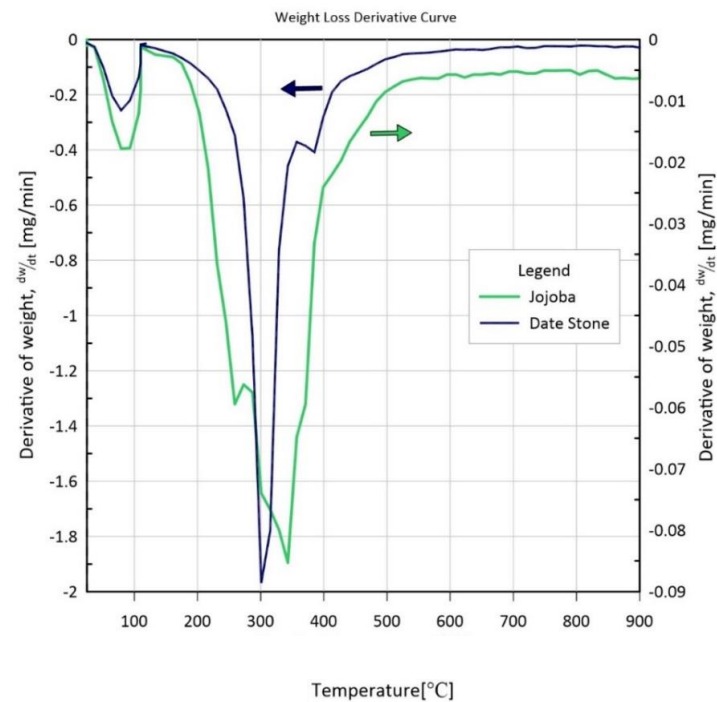


Figure 2. Weight loss derivative for proposed biomass fuels.

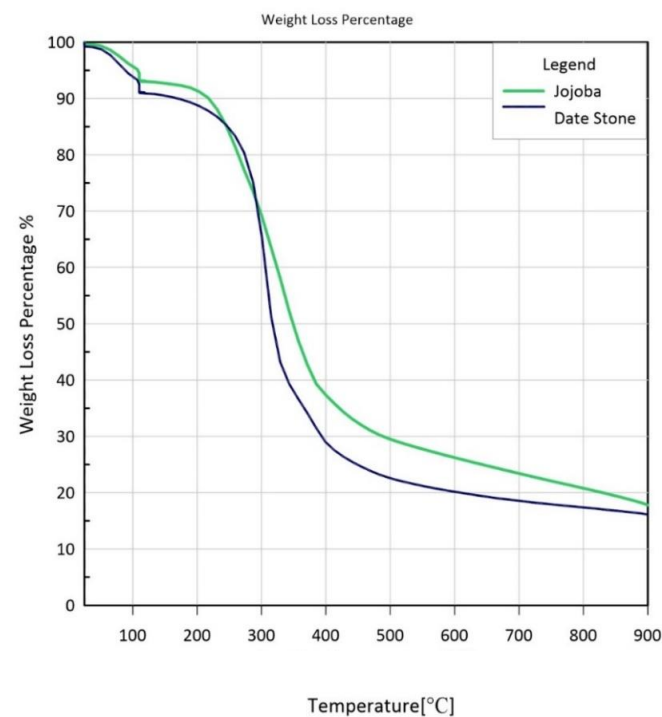


Figure 3. Weight loss percentage for proposed biomass fuels.

Proximity analysis was conducted to calculate the amounts of moisture (M), volatile matter (VM), fixed carbon (FC), and ash based on the weight loss percentage plot in Figure 3. Table 5 shows the comparison between these findings with those from the literature. Compared to date stone, jojoba had lower moisture, volatile matter, and fixed carbon contents than date stone. In terms of ash after burning, jojoba had ash levels that were above 20%, while date stone had 6.4%. The test results reveal that date stone biomass contains higher levels of moisture, fixed carbon, and ash with a lower level of volatile matter.

Table 5. Thermal composition for proposed fuels compared to previous studies, where “M” is the amount of moisture, “VM” is volatile matter, and “FC” is fixed carbon.

Study (Fuel)	M (%)	VM (%)	FC (%)	Ash (%)
Elmay et al. [18] (date stone)	6.4	74.1	17.5	1.2
S.-A.B. Al-Omari [17] (date stone)	7	69	23	1.0
This work (date stone)	8.5	52.6	32.5	6.4
This work (jojoba)	6.8	45.8	26.7	20.7

The expected propulsion performances of the fuels were estimated using the Chemical Equilibrium Analysis (CEA) code developed by NASA [28]. Considering the enthalpy of formation of -967.8 kJ/mol [29] for paraffin-based fuel, -378.72 kJ/mol (28.55 MJ/kg [14]) for date seed, and -95.89 kJ/mol (15.34 MJ/kg [30]) for jojoba, the estimated theoretical combustion temperature for the propellant combination of paraffin/oxygen, jojoba/oxygen, and date/oxygen under the frozen chemical equilibrium condition for a combustion pressure of 2 bar and 10 bar is shown in Figure 4. The maximum combustion temperature at 2 bar was 3384 K, 3406 K, and 3205 K for jojoba, date, and paraffin, respectively, indicating that the biomass fuels have a higher maximum combustion temperature. There was a similar trend between the temperature curves with respect to oxidizer-to-fuel ratio at 10 bar, with 3627 K, 3634 K, and 3433 K as the maximum combustion temperature for jojoba, date, and paraffin, respectively. The maximum temperature occurs at an oxidizer-to-fuel ratio of 0.8 and 0.9 for jojoba solid waste, 0.5 and 0.6 for date stone, and 2.9 for paraffin for each combustion pressure considered. Specific impulse performance (Isp) was also estimated and presented in the figure for the fuels under the two chamber pressure conditions considered. As illustrated in the figure, maximum specific impulse performance occurs at different oxidizer-to-fuel ratios depending on fuel. The maximum Isp was 118 s and 209 s for jojoba solid waste, 115 s and 203 s for date stone, and 132 s and 234 s for paraffin at 2 bar and 10 bar, respectively. Although the combustion temperature was higher for the biomass waste fuels, the fuels had lower specific impulse performance compared to paraffin fuel. The lower specific impulse performance can be explained by a heavier average molecular weight of the combustion products of the biofuels. In this case, it was approximately 29.7 g/mol for date stone, 27.7 g/mol for jojoba, and 19.7 g/mol for paraffin. Different from the oxidizer-to-fuel ratio that maximized the combustion temperature, the maximum specific impulse occurred when the oxidizer-to-fuel ratio was between 0.6 and 0.7 for jojoba, 0.4 and 0.5 for date, and 1.9 and 2.3 for paraffin, depending on the combustion pressure of 2 bar and 10 bar, respectively.

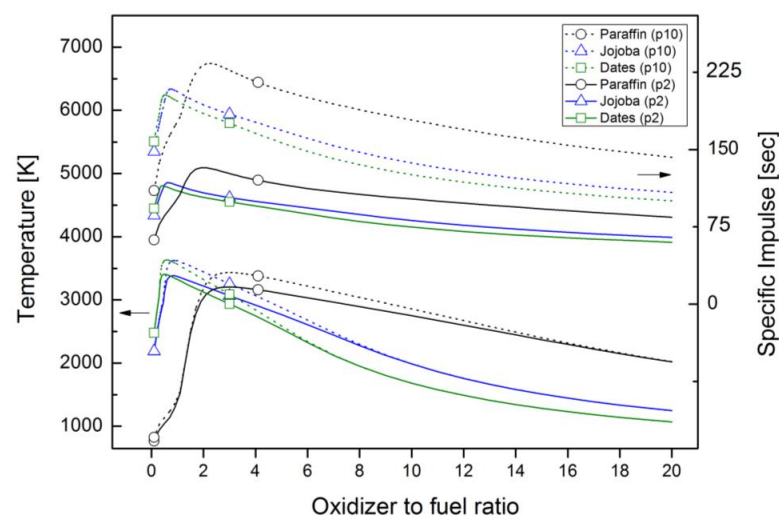


Figure 4. Performance estimation with respect to oxidizer-to-fuel ratio, for combustion temperature and specific impulse performance of date, jojoba, and paraffin, in different chamber pressure conditions of 2 bar and 10 bar (denoted as p2 and p10, respectively).

2.2. Experimental Test Setup

To compare fuel performance, a hybrid rocket was designed and manufactured. The hybrid rocket was designed based on paraffin wax as fuel and gas oxygen as an oxidizer, and the same rocket was used for the biomass fuels as well to compare the performance experimentally under the same testing environment. Figure 5 shows a schematic diagram for the cross-section of the rocket motor components.

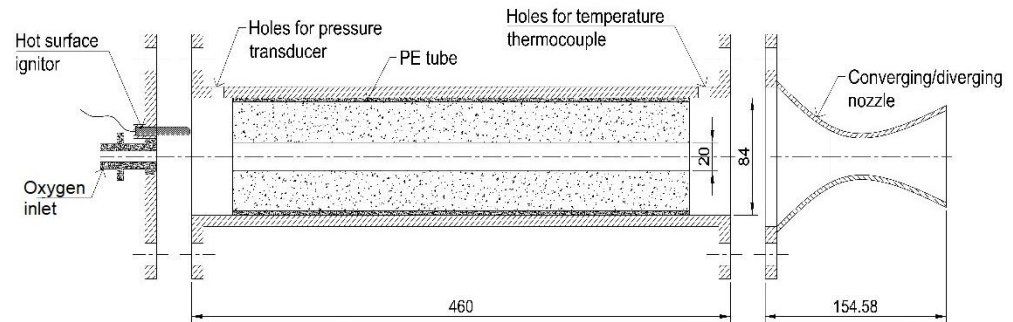


Figure 5. Schematic diagram of the thruster components.

The combustion cylinder was manufactured of stainless steel to endure the high pressure and temperature conditions. The cylinder was 460 mm in length, 84 mm in inner diameter, and 5 mm in thickness. Two holes were made for the oxidizer feeding system and the ignitor through the closing cover, which was made from stainless steel. Two flanges with rubber rings were utilized to join the cylinder with the nozzle and the closing cap. The converging–diverging nozzle was also made of stainless steel. The nozzle shape was conical, as shown in Figure 5, with a total length (L) of 154.58 mm. The nozzle consisted of converging and diverging zones separated by a throat. The length of the converging part of the nozzle (L_c) was 54.84 mm, whereas the length of the diverging part (L_d) was 99.74 mm. The throat diameter (D_t) was 19.49 mm, which was expected to make the nozzle choked with the designed chamber pressure of 2.5 bar. The thruster was not particularly designed to produce a certain targeted amount of thrust, but it was determined based on manufacturing convenience and compatibility of fuel grains. In terms of thrust, however, it was expected to produce a force of approximately 60 N for the paraffin wax/oxygen propellant combination with an oxidizer-to-fuel ratio of 12. The convergence and divergence nozzle had a converging angle of 35° , while the diverging angle was 12° . On the basis of converging–diverging angles, the entrance diameter (D_c), exit diameter (D_e), and optimum exit diameter (D_{eopt}), were 84, 55.10, and 60.48 mm, respectively.

The biomass grains proposed cannot be inserted directly into the combustion chamber due to their weak mechanical structure. Therefore, a compression device was designed and manufactured to strengthen the substance structure to avoid any collapse that could lead to losing the standard shape of the grains with the circular port needed to perform the test. The compression device consisted of a base for the grain's mold to be placed on, and a circular metal rod was inserted to make the grains a hollow shape. A piston of the machine was designed accordingly to press the grains around it with an automated arm using an electric actuator. The fuel was intended to be compressed tightly with the applied compression force until it became sufficiently solid to permit easy removal of the cylindrical rod. The manufactured device is shown in Figure 6. Having coherent grains with proper ports for the oxidizer flow helps to have a better understanding of the regression rate of the grains and the thrust generated. Biowaste fuel grain fabricated by the compression device is shown in Figure 7.



Figure 6. Compression device whole structure (left) and biomass fuel compressed (right).



Figure 7. Date stone biomass fuel grain installed in a combustion chamber.

Contrary to the production process for biomass grains, no compression mechanism was used to create paraffin-wax-based fuel. Due to the weak mechanical qualities of paraffin wax, the fuel grain was developed by mixing paraffin wax in the ratios listed in Table 6 with stearic acid (octadecanoic acid) and carbon nanopowder. Stearic acid is a weak carboxylic acid used with paraffin wax to improve the mechanical qualities of the wax while reducing its fragility [27]. The addition of carbon nanopowder to the mixture enhanced radiative heat transmission between the flame zone and the grain surface [13].

Table 6. Paraffin-wax-based fuel composition.

Ingredient	Mass Fraction [%]	Density [kg/m ³]
Paraffin wax	87	893
Stearic acid	10	850
Carbon nanopowder	3	2130
Paraffin wax binder	100	≈920

The lab-scale hybrid rocket test setup was composed of a lab-scale hybrid rocket, a gaseous oxygen feeding system, a hot surface ignitor, a K-type thermocouple and pressure transducer, an amplifier, a data acquisition (DAQ) system, a force measuring device, a gas

flow meter, and a controller as the system's primary components. For the thrust measurement during tests, a force meter was used to measure the rocket thrust by transferring the data to a PC. A K-type thermocouple was used to measure the temperature inside the combustion chamber and was placed 1.5 cm away from the nozzle. A piezoelectric pressure transducer was placed 3 cm away from the closing cover at the ignition side, sensing the pressure inside the combustion chamber, as illustrated in the schematic depiction in Figure 8.

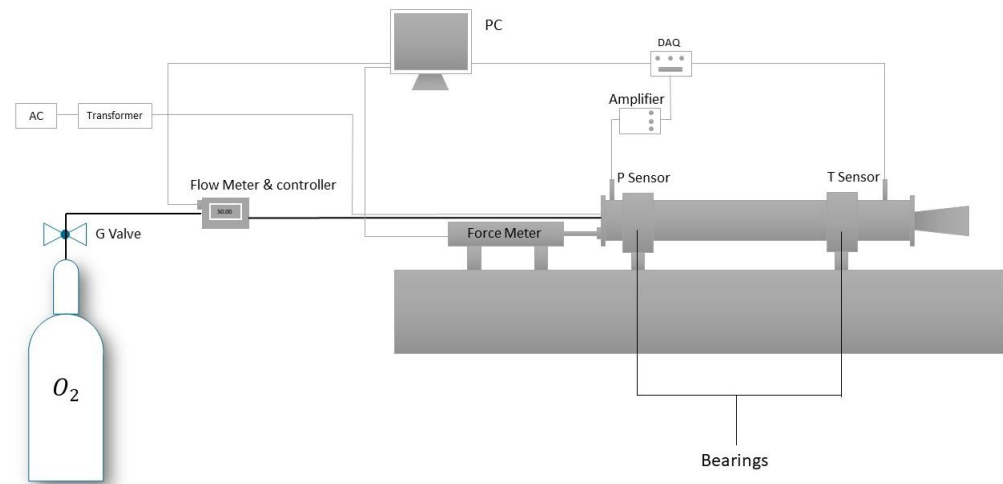


Figure 8. Schematic representation for the setup and experimental apparatus.

Hot surface ignition was used to ignite the grains. Before igniting, a small piece of ethanol-enriched tissue was inserted close to the fuel, making sure the tissue was in contact with the hot surface ignitor to ensure enough energy was released for proper ignition conditions. The AVL piezoelectric pressure transducer, in conjunction with a charge amplifier and a DAQ connected to LabVIEW software 2016, was used to continuously measure the combustion pressure. This software allowed the data to be collected at a rate of 10 kHz and stored in the computer for offline analyses. The oxidizer flow was adjusted to the ignition delay of around three seconds. Before beginning the test, the digital force meter was fastened to the rocket and set to zero.

3. Test Results and Discussion

Combustion chamber pressure and the amount of thrust produced were measured during the experimental performance tests of the date stone, jojoba, and paraffin fuel grains prepared. Each fuel was tested under the same condition with three oxidizer volume flow rates of 80, 110, and 130 lpm. The test results presented successful ignition, combustion, and thrust generation without any issue, but there was a varying performance with the fuels and with flow rates of gaseous oxygen as an oxidizer.

Figures 9–14 present the recorded pressures built up in the chamber and the amount of thrust generated during 30 s of thruster operation. As shown in Figures 9 and 10, in the case of 80 lpm, paraffin-wax-based fuel reached the highest chamber pressure among the fuels used, reaching approximately 2 bar. Combustion pressure for date stone first increased, reaching 1.8 bar, and then decreased until it reached approximately 1.5 bar after about 30 s of operation, while the thrust force increased to 23 N and then fluctuated around 22 N for 15 s. A notable fluctuation took place until the end of the firing. For jojoba fuel, the starting chamber pressure was approximately 1.6 bar, lower than that of date stone, and then it decreased gradually during the 30 s of the firing test, reaching approximately 1.5 bar, a similar end pressure to that of date stone. The average thrust was 22.07 N and 18.08 N for date stone and jojoba, respectively, the performance of which was lower than that of paraffin wax, which had an average amount of thrust produced of 49.44 N. In terms of chamber pressure as well, the biomass fuels reached a lower pressure than paraffin fuel,

which reached approximately 2 bar. Pressure and thrust profiles for the oxidizer volume flow rate of 110 lpm case are shown in Figures 11 and 12. For date stone, the amount of thrust increased to 27 N and the chamber pressure reached approximately 1.85 bar. There was a variation in the chamber pressure and the amount of thrust produced, but they ended with approximately 1.8 bar and 26 N, respectively, with better stability than in the case of the 80 lpm oxidizer flow rate. In the case of jojoba, similarly to the date stone fuel, there was an increase in pressure and the amount of thruster generated. The thrust increased to 33 N and the pressure reached 1.75 bar. Also, the thrust exhibited less fluctuation than that under the 80 lpm oxidizer flow rate. It was notable that the combustion pressure and thrust of jojoba showed slightly lower values compared to date stone propellant under the same oxidizer flow rate condition. Jojoba showed a similar fluctuation to date stone in terms of their thrust profile. However, the date stone thrust profile maintained the same average value until the end of the experiment, while the jojoba thrust had a considerable drop after 20 s of burning. With a 110 lpm oxygen volume flow rate, a higher pressure value, of 2.25 bar, was recorded for paraffin fuel, and it remained almost constant during the burning time. Meanwhile, the thrust profile started at 69 N and was followed by a fluctuating decline until the end of the run, with a consistent drop during the experiment until it reached 60 N. The combustion pressure had better stability at 2.3 bar during the burning time than that of the biowaste fuels.

The combustion pressure and thrust prominently varied in performance by increasing the oxygen volume flow rate to 130 lpm, as shown in Figures 13 and 14. There was a decreasing trend in the amount of thrust generation for the first 15 s of burning time for paraffin fuel. With regards to the chamber pressure, there was a drop in pressure at 24 s. Similarly, an improvement in the pressure and thrust trend was found for date stone at a higher oxidizer volume flow rate of 130 lpm. The thrust increased, reaching almost 40 N, and the chamber pressure increased to 2.29 bar. Both the pressure and thrust profiles were more stabilized. In general, the performance tests of date stone propellant presented an increasing combustion pressure and thrust force, and the same trend was found for jojoba. In addition, it is worth noting that the stability of performance improved with an increase in the oxidizer volume flow rate from 80 to 130 lpm. Regarding the paraffin-wax-based fuel, the chamber pressure tended to be more stable with lower oxygen mass flow rates.

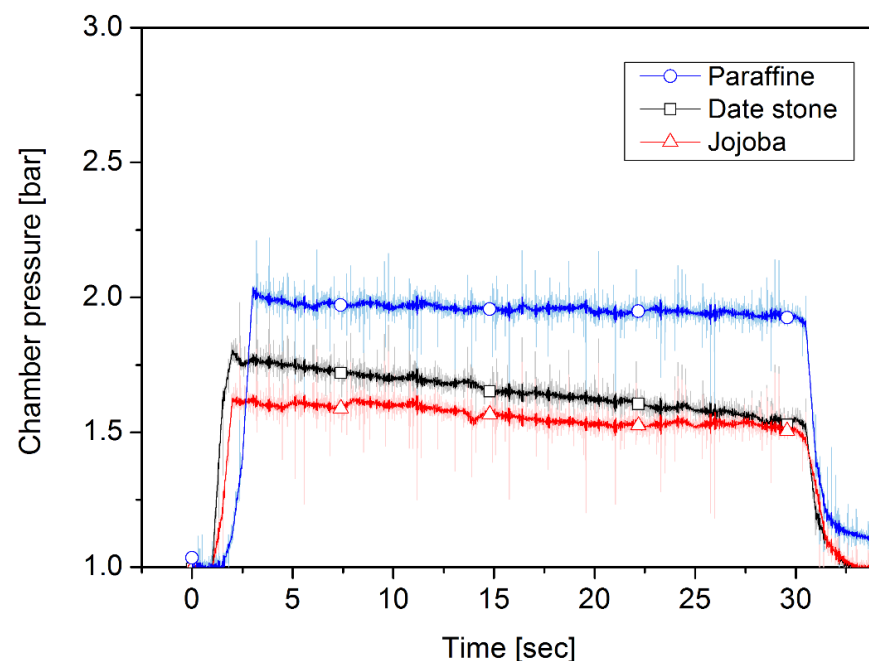


Figure 9. Pressure profile for all tested propellants with oxidizer volume flow rate of 80 lpm.

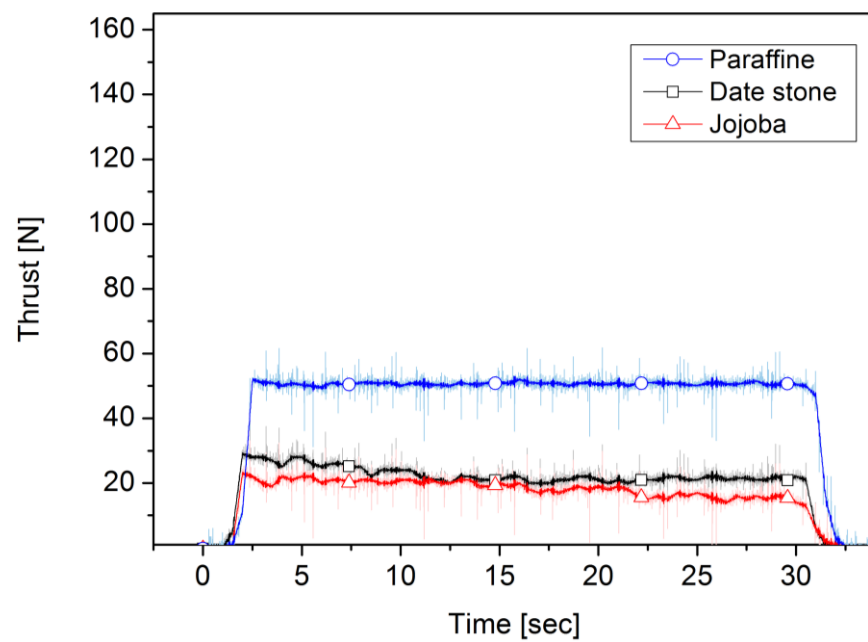


Figure 10. Thrust profile for all tested propellants with oxidizer volume flow rate of 80 lpm.

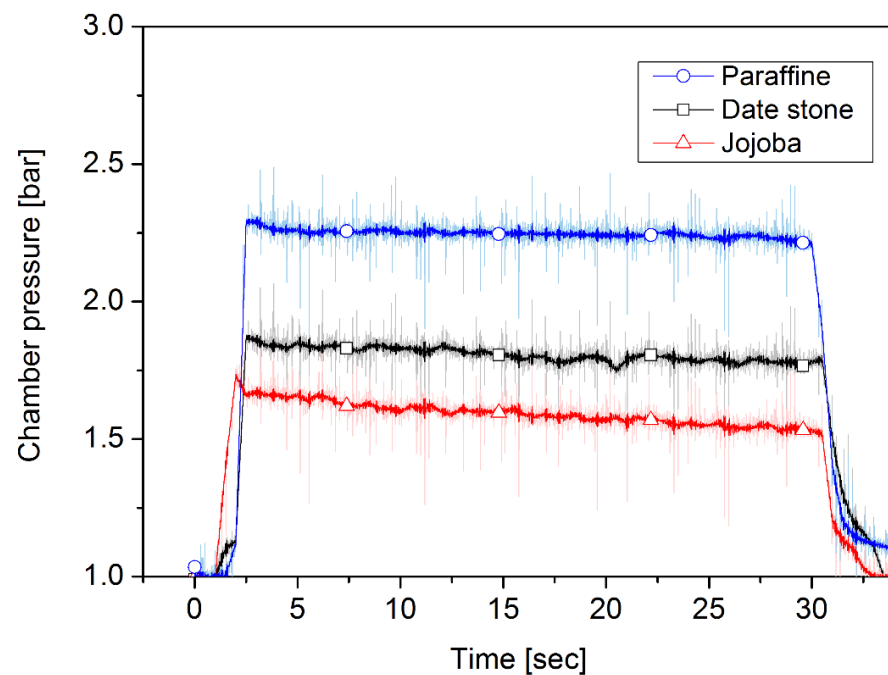


Figure 11. Pressure profile for all tested propellants with oxidizer volume flow rate of 110 lpm.

For lower mass flow rates, date stone and jojoba showed similar performance. However, under an oxidizer volume flow rate of 130 lpm, date stone recorded a higher thrust force compared to jojoba. It is also worth mentioning that under a volume flow rate of 80 lpm, paraffin-wax-based propellant showed more thrust stability while the opposite behaviour took place with higher volume flow rates. The averaged thrust was calculated for all fuels: the highest was paraffin fuel, with 49.44 N, followed by date stone, with 22.07 N, and the lowest value was 18.08 N for jojoba under an 80 lpm flow rate. There were varying performances for each fuel with respect to oxidizer flow rate. Based on the test results, paraffin-wax-based fuel showed better specific impulse and averaged thrust compared to biomass fuels, with the oxidizer-to-fuel ratio higher than approximately 1.5, which was

the criteria to make paraffin more favorable than biomasses, as shown in Figure 4. For the same parameter, date stone generally showed better performance than jojoba.

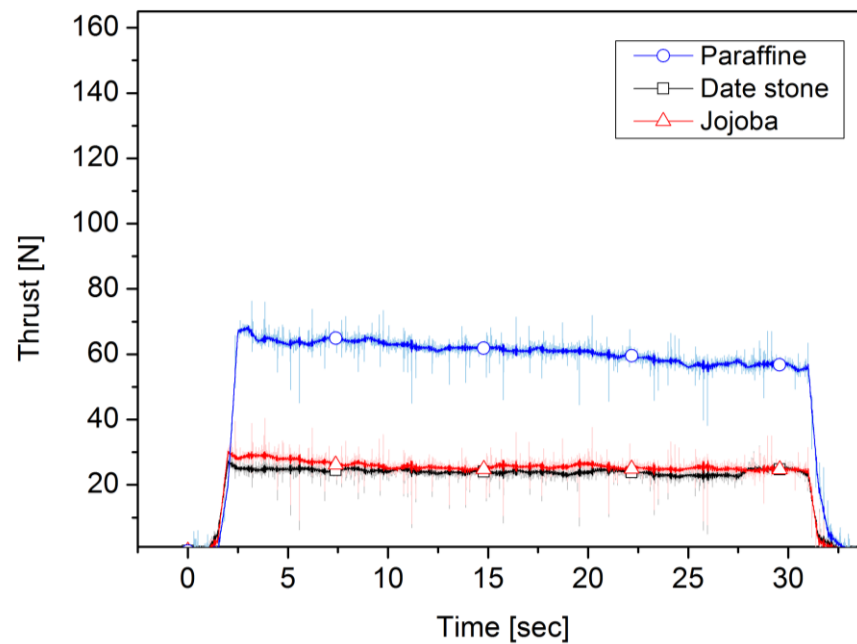


Figure 12. Thrust profile for all tested propellants with oxidizer volume flow rate of 110 lpm.

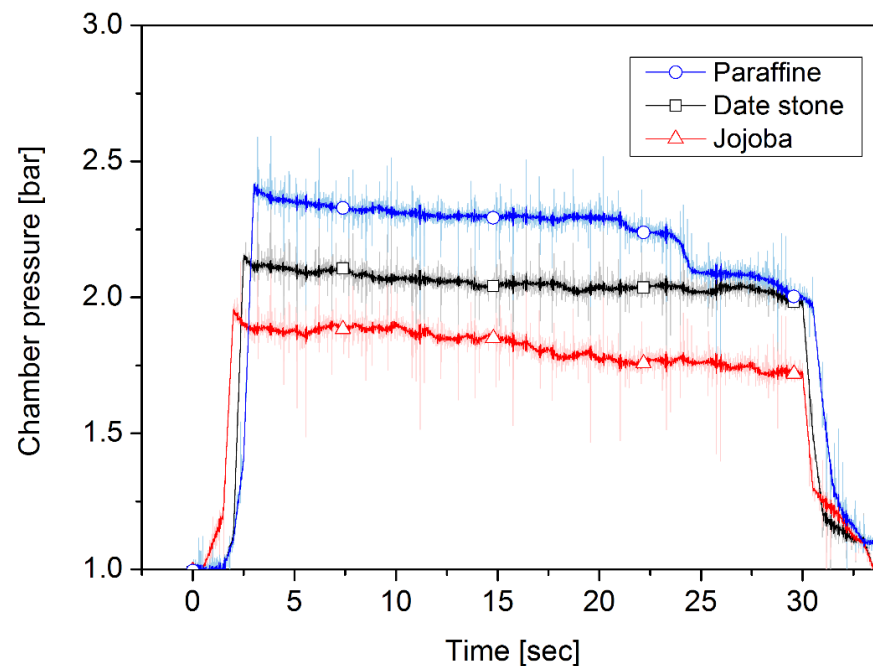


Figure 13. Pressure profile for all tested propellants with an oxidizer volume flow rate of 130 lpm.

For each run, the mass of the propellant grain was measured before and after burning to calculate the mass loss during the test, which was 113 g, 145 g, and 178 g for date; 92 g, 112 g, and 129 g for jojoba; and 171 g, 241 g, and 306 g for paraffin when 80, 110, and 130 lpm oxidizer flow rates, respectively, were supplied. The mass-based O/F ratios were calculated by dividing the oxidizer's mass (m_{GOX}) injected during the testing time by the fuel's mass loss (m_f):

$$O/F = m_{GOX} / m_{fuel} \quad (1)$$

where m_{fuel} is the difference between initial propellant mass (m_i) and final propellant mass (m_f), as shown in the equation below:

$$m_{fuel} = m_i - m_f \quad (2)$$

where m_{GOX} stands for the total amount of oxidizer mass that entered the combustion chamber during the burning process, which can be calculated by multiplying the mass flow rate by the total testing time, 30 s.

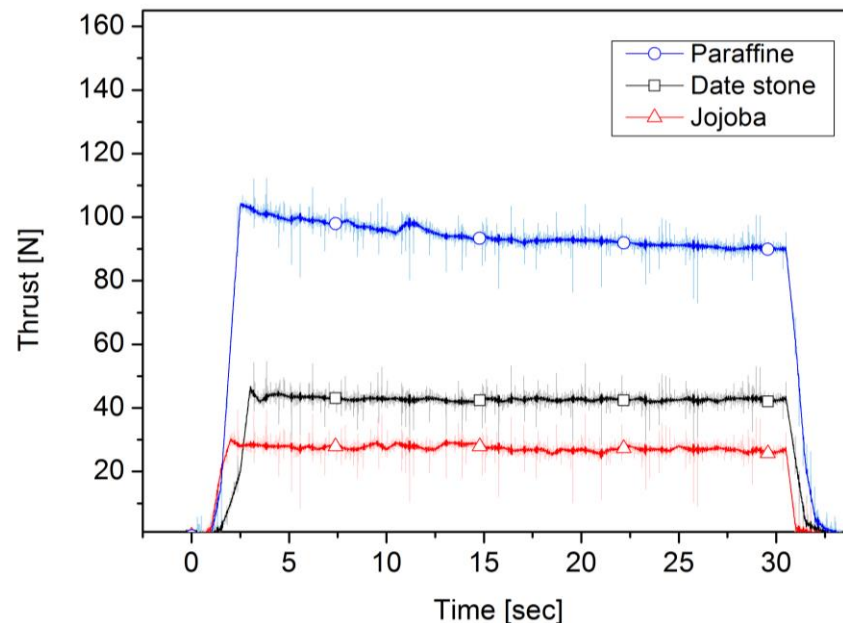


Figure 14. Pressure profile for all tested propellants with oxidizer volume flow rate of 130 lpm.

The O/F ratios for paraffin fuel were the lowest in comparison with other biomass fuels, and the O/F ratios for date stone were lower than those for jojoba. Paraffin fuel recorded an O/F ratio between 6.9 and 7.7, varying depending on the oxidizer flow rate, while jojoba recorded the highest value of 14.2–16.2, and date stone reached 11.4–12.2, lower than jojoba but higher than paraffin fuel. These experiment results are shown in Figure 15, where they are compared with expected thrust performance depending on oxidizer-to-fuel ratio and mass flow rate of oxidizer and fuel consumed during the test, while theoretical specific impulse performance in the case of 2 bar chamber pressure was considered. Similar to the figure, there are expected peak thrusts near 0.6, 0.4, and 1.9 O/F ratios for jojoba, date, and paraffin, respectively. The fuels were not tested with the oxidizer-to-fuel ratio near its optimum; in addition, the expected thrust performance varied depending on the oxidizer-to-fuel ratio, but there was still a discrepancy between expected theoretical thrust and experimental performance. The main cause of the difference stemmed from the difference of chamber pressure for the reference curve estimated under the assumption of 2 bar, while experimental data presented a chamber pressure sometimes higher or lower than 2 bar, although experimental data also showed an increasing thrust trend with respect to increasing oxidizer, and, thus, with total mass flow rate.

Paraffin-wax-based fuel was closer to the optimum O/F ratio than the biofuels and demonstrated superior thrust under all oxidizer volume flow rate conditions considered in terms of the thrust profiles. The performances of date stone and jojoba were similar to each other, but the O/F ratio in testing jojoba fuel was higher than that of date, which caused a larger difference from its optimum O/F ratio, causing lower thrust performance.

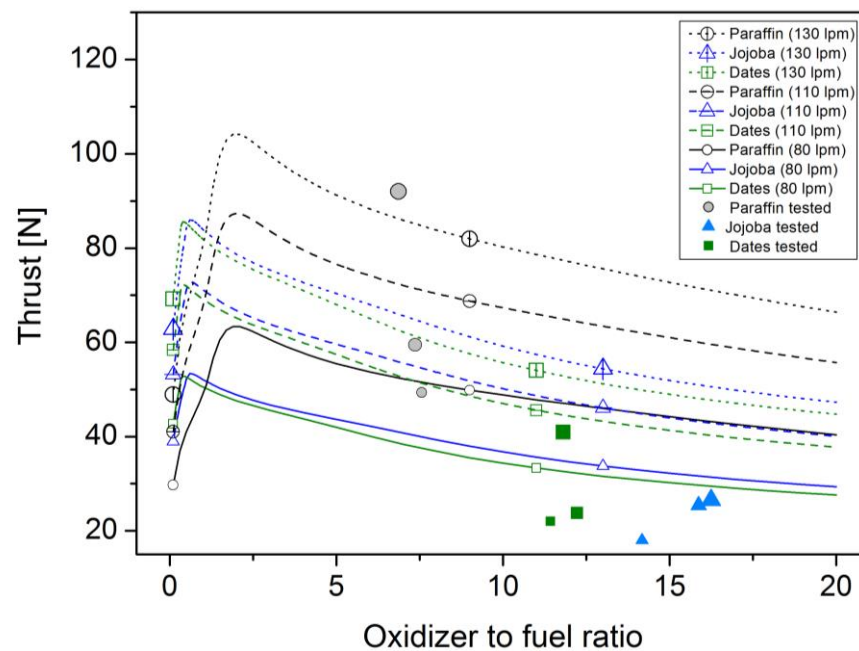


Figure 15. Experimentally tested thrust performance of the fuels with theoretically estimated thrust curves with respect to oxidizer-to-fuel ratio for combustion chamber pressure condition of 2 bar (larger dot size for the increasing oxidizer flow rate of 80, 110, and 130 lpm).

Throughout this study, date stone and jojoba solid waste were employed as fuel grains for a propulsion system and were successfully ignited and tested. The study determined that the tested biofuels can be manufactured in a fuel grain shape compatible with a hybrid rocket chamber, providing sufficient mechanical strength required from hybrid rocket fuel grain; in addition, they are not too soft to be washed away during combustion testing without a participating combustion reaction, demonstrating a stable combustion ability in the hybrid rocket chamber. The results also describe how, despite the same oxidizer flow rate for the same shape of fuel grains, the O/F ratio was different, measuring near 7, 15, and 12 for paraffin, dates, and jojoba, respectively. This implies that the regression rate of dates is lower than that of jojoba, and both biofuels have a lower regression rate than paraffin-wax-based fuel. Although the experimental results determine the feasibility of the biofuels in combustion and propulsion applications, further studies are required on the regression rate characteristics of the biowastes from an optimization point of view. Additionally, investigations are needed on how to achieve the low range of oxidizer-to-fuel ratio that could possibly yield more favorable performance using the biofuel in place of paraffin, as suggested through theoretical performance with respect to oxidizer-to-fuel ratio.

4. Conclusions

Preliminary tests of biomass solid wastes were conducted as fuel grains for a hybrid rocket for propulsion applications. Due to the lack of previously reported data on the regression rate characteristics of the biofuels, they were powdered, compressed, and installed in the combustion chamber for experimental performance testing under the same operating condition as conventionally used fuel, paraffin. Despite their favorable specific impulse performances compared to paraffin in the low range of oxidizer-to-fuel ratio estimated by a theoretical performance study, it was not experimentally demonstrated in this study due to unoptimized fuel grain and a relatively short range of oxidizer-to-fuel ratio to achieve. The experimental test results determined that the biomass wastes can be manufactured as a fuel grain to be compatible with a hybrid rocket combustion chamber. Successful ignition and combustion of the biofuels in the chamber were observed. Regression rate, one of the main performance parameters of a fuel grain, was qualitatively evaluated for the biofuels; the lowest regression rate performance was reported for dates. Both dates

and jojoba were less likely to participate in combustion reactions than paraffin, with lower regression rate performance under the test condition of this study. Although the results were not conclusive regarding their performance, these preliminary data can determine their feasibility as fuel grain for hybrid rocket applications. Further investigations on the consumption rate of the fuels in rocket combustion chambers from a fuel optimization point of view are required to expand the horizon of renewable energy for propulsion applications.

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