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Research Article

Analysis of thermal, chemical and physical properties of paraffin and beeswax blended fuels for hybrid rocket applications

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ABSTRACT

Fuels made of paraffin and beeswax was created for hybrid rocket engines, and carbon, boron, and aluminium powders were added. Scientists used Scanning Electron Microscopy, X-ray Diffraction, and Fourier Transform Infrared Spectroscopy for study of these fuels' thermal, chemical, and physical properties. The fuels were found to form homogeneous mixtures, and key chemical structures were identified. In tests, a beeswax-based fuel blend provided a 15% greater heat of fusion and 10% greater thermal stability than the pure paraffin-based fuels, and improved mechanical and combustion performance compared to the same properties of the paraffin fuels, providing an increase of specific impulse of up to 12%. The results indicate that paraffin / beeswax combinations show promise as a green, convenient and high performance fuel in a hybrid rocket.

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INTRODUCTION

The increasing need for environmentally sustainable propulsion systems has prompted the exploration of bio-derived fuels as safer alternatives to conventional rocket propellants. Traditional solid rocket fuels often contain hazardous chemicals, posing significant risks during handling and combustion. This study investigates the feasibility of using paraffin and beeswax, which are non-toxic and renewable, as hybrid rocket fuels. The research focuses on evaluating the physical, chemical, and thermal properties of these wax-based fuels, enhanced with additives like carbon, boron, and aluminium powders, to optimize their performance. The findings address the demand for safer, high-efficiency fuels employed in small satellite launch systems, sounding rockets, and educational rocket engines, where safety and environmental impact are critical considerations. By characterizing the structural and combustion properties of these bio-derived blends, this work provides insights into their potential applications in modern aerospace propulsion. This paper explores sustainable practices in the design and application of hybrid rocket propulsion systems that use environmentally friendly propellants and fuel additives to minimize the carbon footprint and toxic emissions traditionally associated with rocket

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launches. This paper has highlighted the advantages of hybrid systems that provide cleaner, safer, and cheaper operations than standard solid or liquid propel. The paper has also highlighted the case studies and developments within sustainable propellant formulations that will allow hybrid rocket motors to meet sustainability standards in future designs. The hybrid rocket has been recognized as a transitional technology that can enable more sustainable space exploration and technology development [1]. This paper investigates the environmental impact and performance characteristics of hybrid rocket fuel formulations that have the potential to reduce toxicity, increase performance and to improve the stability of the combustion behavior of the propellant. The paper also explores the use of selected additives and chemicals to increase the regression rate of the fuel, as well as to control the toxic by-products generated in the combustion. Experimental lab tests and simulations show the feasibility of new hybrid fuels and their potential as an alternative to conventional propellants. The investigation is part of a worldwide trend towards greener and more sustainable aerospace technologies and contributes to making space exploration and other space missions less harmful to the environment while maintaining high performance and reliability of hybrid rocket engines [2]. The objective of this study was to investigate the utility of beeswax (BW), an organic compound, as a solid hybrid rocket fuel. BW was combined with ethylene-vinyl acetate and activated charcoal, and the thermal stability and ballistic performance were characterized using thermogravimetry analysis (TGA) and a laboratory scale hybrid rocket motor. The results show that EVA improves thermal stability and AC improves thermal degradation. Despite a marginal reduction in thermal stability, AC has a positive effect on regression rates. The addition of EVA and AC increases fuel viscosity, which influences regression rates. While pure BW has higher regression rates, it burns less efficiently than blends with EVA and AC. This shows that these additives can improve performance, as the combustion efficiency can reach 94% at some additive concentrations. [3] This paper describes research done by students and faculty on the combustion of unconventional bio-derived fuels in a lab-scale hybrid propellant rocket engine (HPRE). The research focuses on lard, paraffin, and beeswax, investigating their non-toxic, non-explosive combustion when combined with various oxidizers, including aluminium powder, as an additive. The primary goals are to determine regression rates and investigate losses from melted, unburned bio fuels to replace conventional toxic and explosive fuels used in NASA-sounding rockets. Over sixty experiments were carried out, with results presented at aerospace conferences. These included regression rate equations for paraffin wax mixed with 10% aluminium powder and a new way to predict fuel losses that haven't been burned by using measurements of exhaust temperature [4].This study looks into the effects of coating nano-sized aluminium powders with different chemical compounds on the regression rate of a reference HTPB solid fuel for hybrid propulsion. Coatings, such as stearic acid, palmitic acid, and esters, have a significant impact on ballistics, with the majority of formulations exhibiting increased regression rates. F-ALEXE coated with an ester significantly improves performance across all oxidizer fluxes. However, the performance of formulations containing stearic acid-coated powders is inconsistent, irrespective of the use of air-passivated or chemically passivated powders. The laboratory coating process is simpler and safer, but environmental factors can influence thermochemical properties. Further research should include numerical simulations to better understand coating decomposition and its interactions with binder pyrolysis and metal oxidation to optimize solid fuel production [5]. The paper builds on a 2010 study that examined the combustion of unconventional bio-derived fuels in a small-scale HPRE. It investigates the combustion of fuels such as paraffin, beeswax, and lard with oxygen, hydrogen peroxide, and nitrous oxide, as well as additives, and calculates regression rate formulas. The research entails designing and testing the HPRE and presenting findings on bee's wax combustion with oxygen at the 51st AIAA Meeting and Exhibit. It describes an indirect method for estimating unburned fuel losses based on combustion product temperatures, demonstrating the HPRE's reliability and establishing correlations between theoretical and experimental variables. The study suggests that oxidizer mass flux can be used as a universally applicable factor for regression rate approximation. It also shows promising results in predicting unburned fuel losses, but these results need to be confirmed by conducting more experiments [6]. An innovative composite fuel containing paraffin wax and LDPE was developed and tested in slab and hybrid rocket motors to study droplet entrainment and combustion properties. The regression rate goes up a lot as the LDPE weight percentage goes up. PR95PE05 has a rate that is 3.9 times higher than HDPE, which makes it burn more efficiently, similar to Stanford University's SP-1a fuel. The chamber pressure spectrum analysis showed that there was no significant instability. This shows that PR95PE05 is a better hybrid rocket fuel in terms of its mechanical strength, combustion performance, and stability [7]. Hybrid rocket technology combines solid fuel combustion with gaseous or liquid oxidizers, providing advantages over conventional solid and liquid rockets. Despite its lower mechanical strength than paraffin wax, people use beeswax, a bio-based fuel, for its environmentally friendly properties. EVA and charcoal are added to beeswax to improve its mechanical properties. Five beeswax formulations containing varying amounts of EVA and charcoal are developed and tested for mechanical properties. The resulting fuel samples have porosity in the range of 0.42-0.84%, indicating high quality. The FTIR analysis confirms that the mixture is uniform without any chemical reactions. Blending beeswax with 20% EVA increases the tensile strength by about 8.1% and elongation to 42%. Furthermore, the addition of 2% activated charcoal increases tensile strength by 8.8% and elongation by 13.4% [8]. A new environmentally friendly hybrid rocket propellant that combines paraffin, stearic acid, and coal.

Mechanical testing at normal and sub-zero temperatures shows that the inclusion of stearic acid and coal increases the propellant's tensile, compression, and flexural strength. Macrostructural and microstructural analyses reveal only minor flaws due to raw material composition and manufacturing methods. Gaseous oxygen-powered hybrid rocket motor firing tests confirm that the new propellant and conventional paraffin-based propellant exhibit comparable specific impulses across varying oxidant-to-fuel ratios. Notably, the absence of hazardous substances such as ammonium perchlorate or aluminium ensures a low environmental impact. Simulation results show that the developed propellant emits negligible amounts of harmful compounds during combustion, making it a promising candidate for low-temperature hybrid rocket technology [9]. A hybrid rocket motor predictive performance model based on thermodynamic and gas dynamic relationships. The MATLAB code was developed using the NASA-CEA equilibrium chemistry code to calculate combustion product gases and an empirical regression rate correlation. Using conservation of mass and the ideal gas law, the model can predict chamber pressure variations and instantaneous performance parameters such as the thrust and specific impulse of the theoretical rocket engine. The model has been verified by comparison with hot-fire test data taken from a laboratory scale hybrid rocket engine that uses paraffin wax fuel and nitrous oxide propellant [10]. The combustion of pure beeswax and beeswax mixed with 10% aluminium powder in a small-scale hybrid propellant rocket engine as part of ongoing research on non-traditional bio-derived hybrid rocket fuels. Beeswax, along with paraffin and lard, is being tested as an alternative to hazardous fuels in NASA-sounding rockets. The study aims to better understand combustion processes, including additives, combustion rates, HPRE operational characteristics, and losses from partially melted bio-derived fuels. Findings from a compact HPRE and testing apparatus were presented at various aerospace meetings. The study presents regression rate formulas for various grain port diameters and evaluates the impact of unburned beeswax losses on combustion. The study also includes a comparison with paraffin wax combustion [11]. The traditional hybrid combustion theory is expanded to include solid fuels that produce a liquid layer when burned. This new theory elucidates how viscosity and surface tension influence droplet entrainment in the gas stream, resulting from the instability of the liquid layer. Entrainment has a big effect on the gasification process, especially in real-life hybrid rocket applications where fuels that melt have faster regression rates than normal materials like HTPB. This theory also applies to solid cryogenic hybrids, explaining the high regression rates observed in cryogenic materials such as solid pentane and oxygen. Stanford University's laboratory experiments confirm the validity of this theory, particularly in paraffin-derived fuels [12]. The combustion of paraffin and paraffin with aluminium powder in a small-scale Hybrid Propellant Rocket Engine (HPRE) is part of a larger investigation into alternative bio-derived fuels. NASA rockets designed these as non-toxic, non-explosive fuels such as paraffin, beeswax, and lard, instead of the customary fuels. This study seeks to better understand the combustion processes, regression rates, HPRE operation, and unmelted biofuel losses. Results from a compact HPRE system were presented at conference proceedings with an aerospace focus. Recent research findings such as regression rate formulas of the paraffin containing 10% aluminium powder and new techniques for prediction of unburned fuel losses within the study's scope [13], such as aluminium, cane sugar and linseed oil, boron and carbon black on paraffin wax-based fuels for hybrid rockets. The melt process and the same additives are in these mechanical strength and thermal properties. Differential Scanning Calorimetry (DSC) and compressive as well as tensile tests show that metallic polyethylene (PE) additives increase the strength, modulus, and burning properties better. DSC analysis found a decrease in melting enthalpy, indicating improved entrainment during combustion. Ballistic tests have indicated that PE reduces regression rates while increasing rates with Al and B and CB additives. In total, these test results indicated that paraffin-based fuels and additives are more effective and often have advantages for hybrid rockets and tactical missiles, because they are more rigid and burn more efficiently [14]. There is some work done on determining the mechanical properties of waxes and hydroxyl-terminated polybutadiene (HTPB), with special attention paid to the quality of the grain structure and its strength. Tensile strength and Young's modulus characterize Among HTPB, tensile strength is the lowest. FTIR and SEM analyzes show that the elongation ratio of beeswax is much higher than that of other beeswax and paraffin wax, along with differing surface morphology. The study stresses the importance of such research in advancing hybrid rocket fuels with their advantages over liquid and solid propellants by weight and structural integrity despite their transport limitations. The mechanical properties such necessary for optimal fuel performance need further research [15].

Boron's in nanoparticle size are suspended into a solid fuel matrix such as paraffin wax fuel. This has been used to investigate the performance of an opposed flow burner in the application of solid fuel-ducted rocket (SFDR) with low boron concentrations to increase the regression rates. Since the agglomerates ejected before combustion and the residues left after combustion have different chemical compositions, hybrid propellant-based SFDR systems can be used in the near future. The combustion behavior and morphological changes of boron-based SFDR systems during combustion can be described using this study as a guide for development and design [16].

The sensitivity test for the combustion behaviour of the aluminium particles between the burnt propellant surfaces and inert walls was conducted with the variation of the propellant surface velocity, propellant surface temperature, radiation temperature, number of parcels, particle diameter, turbulent Prandtl number, and turbulent Schmidt number. The biggest finding in this study was that turbulent numbers had little effect on maximum temperature; however, surface temperature as well as other velocities were found to be sensitive to perturbations, with surface temperature perturbations affecting gas temperature the most. The aim of this study was to understand the effects on the combustion of the solid rocket propellant in down-burning, for computational dynamic modeling and to recommend parameters to be used for determining the effects of the influences [17].

For example, additive manufacturing (AM) techniques such as 3-D printing could be used to create composite solid rocket propellant grains, in which the port geometries of customary casting could be replaced with detailed shapes not limited by mandrels or could vary in shape to achieve greater port burn rates and thrust profiles customized for particular missions. This work has shown that it is possible to produce composite propellant grains with a uniform pore structure and predetermined porosity levels. The process can be applied to rocket propulsion systems, pyrotechnics, and explosives [18].

Here is the complete history of solid propellant, its development and future prospects. The military background of solid rocket propellant systems and perceptions that the technology for solid rockets had not progressed greatly were reasons for favoring liquid propellant systems in space propulsion. The entrepreneurial drive in solid rocket development is highlighted, as is the contribution of key organizations such as Thiokol and Aerojet.

Despite the challenges, additive manufacturing opens up new possibilities for solid propellant design, such as custom port geometries and controlled porosity, which could revolutionize propulsion systems. The paper also addresses common misconceptions about the safety and reliability of solid rockets in comparison to liquid alternatives, emphasizing the continued importance of solid propellants in military and space applications. Looking ahead, the solid-propellant industry faces shifts in focus, material supply challenges, and the need for new expertise, all of which present both obstacles and opportunities for solid rocket technology innovation [19]. A new solid fuel for hybrid rockets that combines paraffin wax with 5% (SF4) and 10% (SF-10) LDPE demonstrated improved combustion performance, with higher regression rates and efficiency when compared to polymeric and pure paraffin fuels. SEM revealed homogeneous blends, whereas TGA confirmed the immiscibility of components during degradation. DSC data showed that higher paraffin content reduced LDPE melting temperature, whereas blended fuels with lower paraffin wax had lower total specific melting enthalpy, consistent with the additive rule. It was also found that as LDPE loading increased, the linear coefficient of thermal expansion decreased. Thus, a new composition of rocket fuel with low LDPE loadings was made, unlike customary phase change materials [20]. This propellant experiences some issues in manufacturing due to the low tensile strength and bonding mechanism, but the regression rate of the paraffin-based fuel is much greater than that of customary hybrid rocket fuel, three to four times greater. To address this, EVA was combined with paraffin-based fuel to reduce shrinkage while increasing tensile strength. The experiment revealed that adding EVA increased maximum strength by approximately 1.6 times and maximum strain by up to 2.2 times at a 20% EVA concentration. However, at the same EVA content level, a 35% decrease in the regression rate accompanied this strength increase [21]. The aim of the study was to improve the mechanical properties of the wax used in the hybrid rocket system with EVA. As the wax-EVA mixture hardened, its mechanical properties got better. For example, a blend of 20% EVA and 80% wax could stretch about 17%, while pure wax could only stretch 4%. Higher EVA content was associated with improved mechanical performance. Regression rate studies showed that EVA addition decreased the regression rate, countered by the presence of the bluff body at the front end. It was found that the regression rate of fuels containing 20% EVA and 80% wax was less than that of pure wax but three and a half times that of polymeric fuels [22]. The main goal is to highlight the importance of SEM in explaining the differences between physical and mechanical properties of the improved clays before and after improvement. Clays pose challenges in the construction industry because of their low strength, high compressibility, and swelling potential. Traditional interpretations of clay's behaviour may not be entirely consistent with their properties, necessitating microstructural analyses. The SEM has been used in the study of microstructure of clays and additives, and is used here to investigate microstructural properties of the modified clay. This gives researcher's new information about how clay particles and additives behave, which could help them explain physical or mechanical phenomena they didn't understand before [23]. Ever since the Chinese first developed primitive powder rockets in the 13th century, the notion of reaction propulsion has captivated the human race. This propulsion system utilizes ejected matter to facilitate motion. Despite the advancements in rocket propulsion, a lack of understanding of propellant combustion characteristics has impeded scientific progress in reaction propulsion. Propellant formulation, testing and use, however, will remain empirical until the physicochemical mechanisms are well characterized. Conventional composite propellants are heterogeneous mixtures of a crystalline oxidizer (ammonium perchlorate or ammonium chlorate), a polymer fuel binder and metal fuel dopants. The combustion of composite propellant is a complex process, due to the interaction between the different components of the propellant and the combustion wave. Scanning electron microscopy (SEM) can be a useful tool to investigate how the ingredients interact with each other and provide additional information about the combustion mechanism (the clustering of the metal particles, the dissociation of the oxidizers and the interaction between them). Therefore, the aim of this article is not only to show the usefulness of this SEM study on solid propellant combustion, but also to show the complexity of this field of study, and recommend more wide-ranging works on propellant combustion [24]. Systems under study used hydroxyl-terminated polybutadiene as binder and were analyzed before and after accelerated aging. Isothermal aging tests have been conducted at temperatures of between 65 and 85 degrees Celsius. Fourier transform infrared spectrometry and scanning electron microscopy by X-ray scattering were employed to investigate the impact of accelerated aging on solid fuel samples. The utilization of infrared spectrometry yielded valuable insights into the impact of temperature on the functional groups associated with the binder and oxidant within the examined formulations. The SEM/EDX analysis facilitated the examination of the morphology of representative material samples at both the micrometric and sub-micrometric scales [25]. The Combustion Research Laboratory at the University of Arkansas at Little Rock (UALR) uses non-intrusive spectral techniques and a Fourier Transform Infrared interferometer to study flame sources. The laboratory has previously found several problems trying to use emission spectroscopy as an analytical tool of nonsteady sources due to flickering (pulsing) as an interference frequency in sources such as the UALR Hybrid Rocket plume. A mathematical model of the interferometer and its interaction with these interference frequencies was created and simulated in MATLAB software. This simulation allows for the prediction of the amount of noise that source intensity fluctuations will introduce into the IR signal. Several researchers have developed mathematical relations between the interference frequencies in the time domain of the interferogram and in the frequency domain of the spectrum [26]. X-ray diffraction characterizes crystalline samples using an important non-destructive technique because the technique determines their chemical composition, crystal phases, texture, average crystallite size, crystallinity, strain, and defects. X-ray scattering from lattice planes in the sample constructively overlaps at certain angles to produce diffraction peaks. The intensities of these peaks depend upon the atomic structure of the lattice. As a result, XRD patterns are useful for identifying periodic atomic configurations. This review summarizes recent advances in XRD techniques observed in a variety of fields over the last five years, including pharmaceuticals, forensic science, geology, microelectronics, the glass industry, and corrosion analysis [27]. Carbon nanomaterial research has increased dramatically in recent decades as a result of their numerous applications. The effect of paraffin wax soot, carbon black precursors, and the new manufacturing processes on the soot microstructure was studied. Structural and morphological investigation of soot samples was carried out by X-ray diffraction (XRD), and High Resolution Scanning Electron Microscopy (HRSEM) combined with Electron Dispersive Spectroscopy (EDS). There are distinct differences in the mean lateral dimensions of the aromatic lamellae, the stacking height, the average 002 plane spacing (d(002)), and the degree of aromaticity between paraffin wax soot and carbon black.They have low levels of disorder, evidenced by a low ratio of γ to band intensity. Scanning electron microscopy (SEM) images show carbon Nano sphere particles which are not uniform with a size range between 26 and 94 nm [28].

LITERATURE REVIEW SUMMARY

The exploration of bio-derived fuels, particularly paraffin, and beeswax, as alternative propellants for hybrid rockets has gained considerable attention due to their environmental benefits, cost-effectiveness, and safer handling properties Based on the Studies by Soojong Kim et al. [7] and Viatcheslav Naoumov et al. [11]. Several studies have been performed to investigate the use of fuel blends with additives such as aluminum, carbon and boron to improve combustion efficiency and increase mechanical strength, as shown in works by Syed alay hashim et al. [16] and Shinya Maruyama et al. [21]. Moreover, research conducted by Ural et al. [23] and Tudor Tiganescu [25] on fuel morphology and structural behavior using Scanning Electron Microscopy and Fourier Transform Infrared Spectroscopy has highlighted the role of additive composition in enhancing thermal stability. Despite these advancements, several limitations persist. Past studies by R.arun Chandru et al.[18] and Sri Nithya Mahottamananda et al.[8] often lack comprehensive characterization of fuel blends that combine multiple bio-derived waxes, and few provide detailed comparisons of the physical and thermal performance of these blends under hybrid rocket conditions .Also research by Andrei A. bunaciu et al. [27] and Anu N mohan et al. [28] have limited research on the direct influence of crystallinity and chemical bonding patterns, as revealed by X-ray Diffraction, on the combustion and stability of these bio-based fuels. To address these gaps, the present study systematically examines paraffin-beeswax fuel blends enriched with carbon, boron, and aluminum additives. Through the use of SEM, XRD, and FTIR analyses, the study provides a deeper understanding of how these components affect fuel morphology, thermal behavior, and combustion efficiency, offering new insights for advancing bio-derived fuels in hybrid rocket applications. This study offers an innovative perspective on the development of hybrid rocket propulsion through the exploration of bio-derived fuels, specifically paraffin and beeswax blends enhanced with carbon, boron, and aluminum powders. The majority of conventional solid rocket propellants are toxic and/or hazardous. In contrast, this study focuses on environmentally friendly and non-toxic bio-fuels. It presents an exhaustive study of bio-derived propellant compositions using advanced analytical techniques such as scanning electron microscopy (SEM), x-ray diffraction (XRD), and Fourier transform infrared (FTIR) analysis to provide perceptions into their structure, thermal and chemical properties. Lastly, this study seeks to investigate the synergistic effect of additives on the thermal stability and combustion performance of solid paraffin and beeswax fuels in order to optimize their use in hybrid rocket propulsion systems. The results from this study may help improve sustainable aerospace technology and the development of energy platforms for a safer and greener aerospace system.

MATERIALS AND METHODS

Fuel and Additives Selection

Paraffin wax mixes saturated hydrocarbons named alkanes. Alkanes have the molecular formula CnH2n+2, with n = number of carbon atoms in the alkane. At room temperature, paraffin wax hydrocarbons go from n = 20 up to n = 40. Its hydrocarbons have an average molecular weight of. That weight ranges from 300 to 600 g/mol.

This long straight-chain carbon-based polymeric structure gives the resulting polymer its crystalline structure and thermal properties. The selection of additives such as carbon, boron, and aluminum powder as well as potassium nitrate was based upon their ability to improve specific performance attributes, such as thermal stability, specific impulse, and combustion efficiency. Carbon was chosen due to its thermal conductivity, which distributes the heat uniformly over the fuel surface, increasing its regression rate and combustion stability. Boron was selected because of its high heat of combustion. This increases the flame temperature and energy density of the propellant. This optimizes the thrust and specific impulse. Aluminum has a high energy density. It also contributes a lot of heat and stabilizes the combustion process. Residue clumping needs control. Potassium nitrate acts as an oxidizer to provide additional oxygen. It also improves the fuel's performance. The above additives were chosen as they fit the criteria for hybrid rocket propellant additives which maximize the energy released and supply a steady burn, thereby improving performance.

Preparation of Fuel Samples

Beeswax and paraffin wax were used in the fuel samples with carbon, potassium, borax and aluminium powder as additives. The required amounts of wax and additives were weighed out, then ground down to powder in a pestle and mortar, and finally mixed together to create the fuel mix.(Table 1) The mixture of molten fuel was then poured into the mould. It was stirred to prevent the formation of voids and air bubbles, then left overnight to harden. The hybrid rocket motor is a rocket variant combining solid and liquid or gaseous propellants together. The oxidizer exists as a liquid or as a gas. It is injected within the combustion chamber, where it reacts with the solid fuel grain. A schematic of a hybrid rocket motor appears in Figure 2.

Combustion of Wax-Based Fuels in Hybrid Rockets

This simplicity and higher safety margin, controllability, and the lower environmental impact compared to solid propellant rockets, which often use highly toxic propellants, have led to hybrid rockets becoming popular for research and suborbital and space tourism applications. Even though these engines have certain advantages, the trade-off in performance losses, combined with inconsistent combustion stability, has meant that they have not gained much prominence in heavy-lift rockets, compared

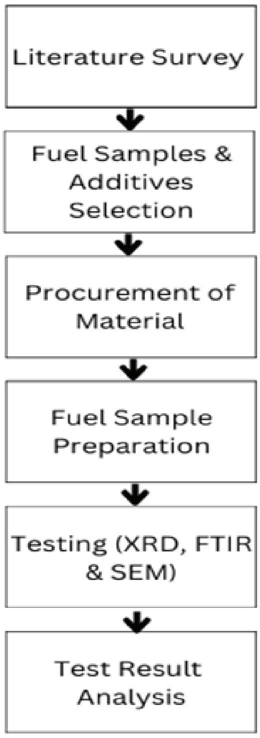


Figure 1. Process Flow Chart.

to pure liquid rocket engines or solid rocket engines. A hybrid rocket motor is a type of rocket engine that burns a solid fuel with a separate stored oxidizer, liquid or gaseous. The oxidizer enters the combustion chamber during operation then flows through the solid fuel. Someone ignites the solid fuel. This reaction combusts, creates hot gases as it vaporizes the solid fuel, and mixes it through the oxidizer inside the combustion chamber. The combustion gases are expanded through the nozzle to produce thrust. The mass flow rate of oxidizer can control the thrust, allowing the rocket to throttle as well as (in the case of hybrid fuel) shut down during flight. This allows the hybrid rocket to combine the simplicity and intrinsic safety of the solid rocket with the throttle and steering capability of the liquid rocket. For hybrid rockets, wax-based fuels are burned with solid, liquid, or gaseous propellant. Hybrid rockets typically use solid fuel with a gaseous oxidizer, using either oxygen or nitrous oxide, with wax the typical fuel component. The igniter lights the solid fuel grain in the combustion chamber to create thrust. The heat from the igniter melts a thin layer of wax upon the surface, which forms the liquid fuel as it melts. This means the oxidizer flows over the melted wax. The burning process vaporizes the wax, and it mixes with the vaporized fuel in order to burn during a combustion reaction (Properties of fuel samples shown in Table 2, Fixed and variable parameters are shown in Table 3). This produces hot gases that are then rapidly expanded to provide thrust. The high regression rate of paraffin based fuels is one of the reasons those are the preferred fuels. The rate at which the burning surface of the solid fuel recedes is determined by heat transfer to the fuel, the viscosity of the melted layer, and the interaction between the vaporized fuel and oxidizer. The gases produced by the combustion reaction expand and are ejected through a nozzle at high speed, producing thrust according to Newton's third law. The nozzle design plays a crucial role in optimizing the thrust produced by the engine.

Table 1. Fuel samples composition

Fuel Sample	Beeswax	Paraffin Wax	Carbon Powder	Aluminium Powder	Borax Powder	Potassium Powder
40BW10C40A10B	40%	-	10%	40%	10%	-
40BW10C40P10B	40%	-	10%	-	10%	40%
50BW40A10B	50%	-	-	40%	10%	-
60BW15P10B	60%	-	-	-	10%	15%
0BW10C20B	70%	-	10%	-	20%	-
40PW10C40A10B	-	40%	10%	40%	10%	-
40PW10C40PN10B	-	40%	10%		10%	40%
50PW40A10B	-	50%	-	40%	10%	-
60PW15P25B	-	60%	-	-	25%	15%
70PW10C20B	-	70%	10%	-	20%	-

Table 2. Properties of Fuel samples

Properties	Beeswax	Paraffin Wax	Carbon	Aluminium	Borax	Potassium
Density (kg/m^3)	970	900	80	2,710	1730	862
Melting Temperature (°C)	62–65	59–63	3652-3697	660.37	743	63.25
Molecular weight (g/mol)	676	380	12	26.98	381.37	39.09

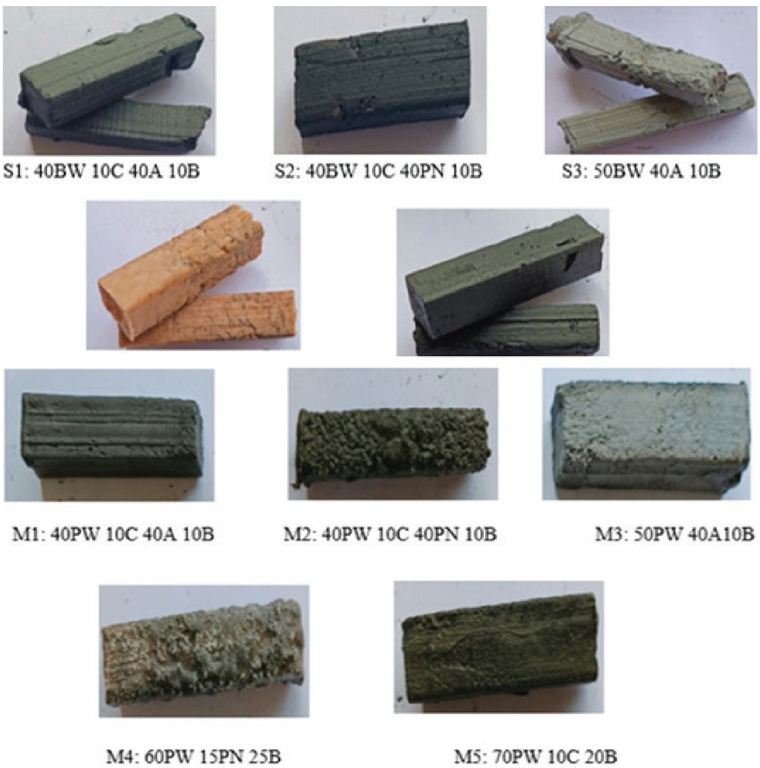


Figure 2. Blended Fuel Samples.

Table 3. Fixed and variable parameter

Parameter Type	Parameter	Description
Fixed Parameters	Fuel Type	Paraffin wax and beeswax, composition fixed per sample
	Oxidizer Type	The type of oxidizer used remains consistent (e.g., liquid oxygen or nitrous oxide).
	Combustion Chamber Dimensions	The dimensions of the chamber are fixed to maintain uniform testing conditions.
	Ambient Pressure	The experiments are conducted under the same atmospheric conditions.
Variable Parameters	Additive Concentration	The percentage of carbon, boron, and aluminum powders added to the fuel
	Oxidizer	The rate at which the oxidizer is injected into the combustion chamber.
	Fuel Grain Geometry	Variations in the shape and size of the fuel grains to observe performance changes.
	Temperature	Initial temperature of the fuel and oxidizer, which can vary to assess thermal behavior

Experimental Methods

XRD set-up details

An X-ray diffraction Spectrometer is an apparatus utilized for conducting X-ray diffraction analysis on diverse materials. This is an effective instrument for examining the crystallographic characteristics of solids, liquids, and powders. XRD instruments yield critical insights into atomic arrangement within a material's lattice, crystal structure, phase composition, crystal orientation, and additional structural attributes. Benchtop-type XRD machines were brought into use and samples were provided in powdered form. Specifications of the XRD machine used are:

- Cu Kα radiation
- Minimum Step Size: 0.02519
- Angle Range: 5° to 140°
- Detector Mode: Scanning line detector (one-dimensional), Static line detector (one-dimensional)

FTIR set-up

FTIR is applicable to organic as well as many inorganic materials and can determine covalence and functional groups. It has been used in the characterization of solid rocket propellant formulations and is an important tool in this field. FTIR has been applied in establishing standards and specifications for solid propellant formulations in respect to quality, performance and safety. The propellant formulation is a very complex mixture of oxidizer, binder, stabilizer, and additives. FTIR has been used to check the presence of the molecular fingerprints of the chemical components and formulations.

These species are contaminants or degradation products, and their presence can be used to determine propellant long-term stability. FTIR can also be used to monitor functional groups in propellant such as nitro or hydroxyl functional groups. The samples were given in powdered form. The specifications for the Fourier Transform Infrared Spectroscopy (FTIR) machine used are:

- Spectral range: 500 to 7500 cm^{-1}.
- Spectral resolution: Superior to 2 cm^{-1}.
- Precision of wave number: Superior to 0.01 cm^{-1}.
- Detector: DTGS.
- Rock Solid Interferometer: Gold mirrors (permanently calibrated).
- Holder: Standard sample mount measuring 2×3 inches, suitable for pellets as well.
- Accessory necessary for ATR configuration.

SEM set-up

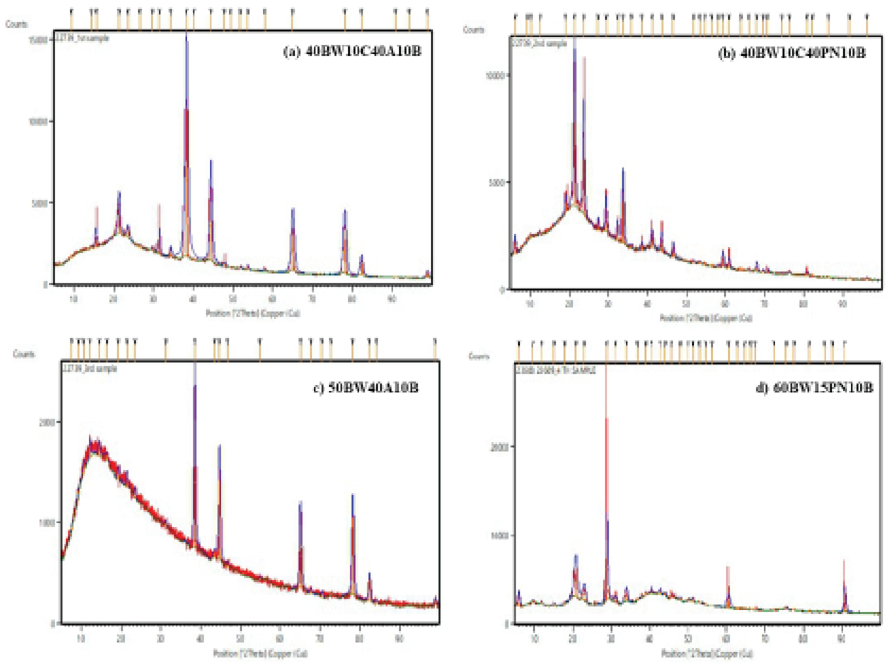
In Scanning Electron Microscopy (SEM), a beam of focused electrons scans across the surface in a sample and emits secondary electrons, backscattered electrons, and characteristic X-rays that detectors find so they produce high-resolution images and obtain compositional information. Secondary electrons provide information on surface topography. Backscattered electrons give atomic contrast, together with X-rays providing chemical composition. These signals work in conjunction to let the SEM make detailed images and do material analysis. To prepare for the SEM analysis, the sample was crushed, dried in the laboratory oven, and a small amount from the sample was placed in the machine under the SEM alongside other samples. The SEM machine has various modes, which include Imaging modes (Standard, HR-SEM, STEM, dispersion mode, Opti-mode (magnetic samples), Low vacuum, EDX & Elemental Mapping).

RESULTS AND DISCUSSION

The chemical properties of paraffin and the additives carbon, boron, and aluminum allow paraffin and beeswax blend fuels to meet the performance requirements of hybrid rocket engines. Paraffin wax has a very high regression rate because the melt layer of wax that coats and cools the fuel surface evaporates rapidly, allowing the fuel to vaporize more easily. Despite the lower regression rate of beeswax, attributed to its more complex esters and fatty acids, its thermal stability and stability of its structure make it valuable. The thermal conductivity and the regression rate can be improved by the use of carbon and boron, and aluminum is best known as a high-energy additive. The effect of adding metal to the wax-biopolymer mix in hybrid rocket propellant results in an important increase in regression rates, according to Karabeyoglu et al. [12] and Hashim et al. [16]. The wax blend provides high combustion efficiency because of the clean-burning hydrocarbon chains of wax and high thermal stability of beeswax. Further, FTIR analysis of product gases indicates that the presence of covalent carbon-hydrogen bonds in the mixture improves combustion and increases the calorific value. It has been shown that the flame acceleration and energy density of the mixture can be improved by the presence of additives such as aluminum and boron [4, 20]. The thermal stability of beeswax prevents softening and deformation before the operation temperature. The tensile and surface strength of the waxes is greatly increased by activated charcoal and/or EVA (Ethylene-Vinyl Acetate) copolymers. Non-toxic and environmentally friendly nature of the wax blends make them preferred alternative propellant types for hybrid rocket propulsion systems. A better combustion of the wax fuel blends can be achieved by adding aluminum powder into paraffin and beeswax fuels instead of carbon or boron. Due to its high energy, aluminum substantially increases the heat produced during combustion. This increases the regression rate and stabilizes the flame, which increases the thrust and specific impulse of the motor greatly. Other doping elements such as carbon mainly increase the thermal conductivity of alumina, boron can increase the ignition and flame temperature, aluminum can be preferred, but the use of aluminum can reduce thermal efficiency in terms of the combustion temperature gradients that can be created. The aluminum residues can also agglomerate. This can lead to reduced combustion efficiency and residues that require appropriate disposal or treatment. Aluminum is still widely used for high-energy propulsion. Stability and energy production of wax-based fuels strongly depend on the structure of monoesters, n-alkanes, and fatty acids they contain. Unlike other waxes, the higher thermal stability of the monoester bonds in beeswax is due to the fact that they break down at a higher temperature and produce non-toxic byproducts. Stable long-chain n-alkanes, which are the main components of paraffin wax, are well suited for combustion because they oxidize cleanly and liberate a lot of heat when burned, as their linear structures allow them to burn smoothly. Fatty acids, although non-energetic components of beeswax with other helpful additives, provide oxygenated fuels of lower energy density to the fuel blend. The n-alkanes, fatty acids and monoesters are thus blended to achieve an optimum combination of high energy density, thermal and combustion stabilities to provide stable and efficient operation at the temperature and pressure extremes of the combustion chamber and sustain the operation of the rocket engine.

XRD Results

X-ray diffraction or XRD analysis determines the crystalline structure, phase composition, and crystallinity of paraffin wax and composite fuel samples. XRD analyzes samples. The sample is irradiated by a monochromatic X-ray beam, and the resulting diffraction pattern is used to determine the atomic structure, phases, and the crystal grain size and shape (Table 4). Other than being useful for identifying crystal phases, XRD may be used for characterizing the solid state of paraffin wax, confirming the results of a SEM study, and distinguishing between different waxes, such as paraffin and beeswax. It may also be used in fuel systems, and production quality control. Paraffin waxes consist of the paraffin fractions with relatively pure long-chain alkanes and well-ordered crystalline structures. Its XRD spectrum is consistent with this, while the more complex mixture of esters and fatty acids in beeswax is less ordered. The structure of hybrid rocket fuel can have a major influence on fuel thermal stability and combustion. (Figure 3)



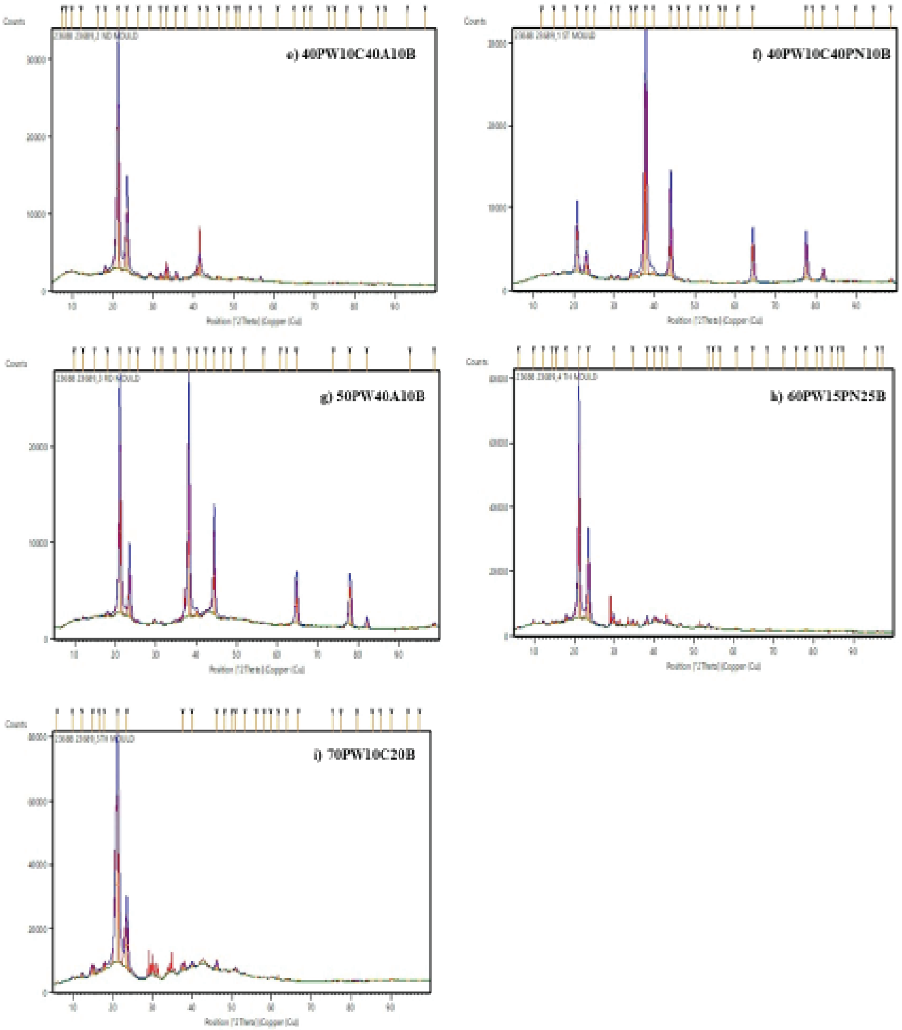


Figure 3. X-Ray Diffraction Pattern.

Table 4. X-Ray Diffraction results

Fuel Sample	Diffraction Angle (2Θ)	Bragg Angle (Θ)	Lattice Spacing (d-spacing) (A^0)	Miller Indices
40BW10C40A10B	38.49	10.20	5.01	100
40BW10C40PN10B	21.40	10.09	5.03	100
50BW40A10B	38.53	12.44	5.07	100
60BW15PN10B	29.91	10.02	5.09	100
40PW10C40A10B	37.76	12.22	5.01	100
40PW10C40PN10B	21.29	10.00	5.03	100
50PW40A10B	38.18	10.26	5.09	100
60PW15PN25B	21.18	10.33	5.01	100
70PW10C20B	21.00	10.75	5.03	100

The research on the x-ray diffraction for the crystalline property of wax types is very important. The knowledge gained from the analysis is further helpful in the future to understand the wax material properties, its effects on the hybrid rocket applications and the quality and performance of the hybrid rocket fuel systems.

FTIR Results

Besides providing a means to characterize the chemical species and bonding present, Fourier Transform Infrared Spectroscopy (FTIR) can be used to study the aging or degradation of propellants to provide an indication or comprehension of the long-term thermal or environmental aging stability of the propellant under investigation. FTIR is widely used for reliability and quality assurance applications as it is non-destructive, quick and highly accurate for the analysis of solid rocket propellants.

The samples with paraffin wax base (from 40PW10C40A10B-60PW15K25B) had values ranging from 2900.94 to 2904.8, and those with beeswax base (40BW10C40A10B-S5) from 2908.65 to 3668.61 (Table 5). The samples without aluminum differed only slightly in their values and those with paraffin wax base of 60% and 70%. The beeswax samples' values ranged from 2908.65 for 40BW10C40K10B to 3668.61 for the highest valued sample, 40BW100C0K20B. Potassium nitrate (KNO_3) addition decreased the peak value dramatically. The values of

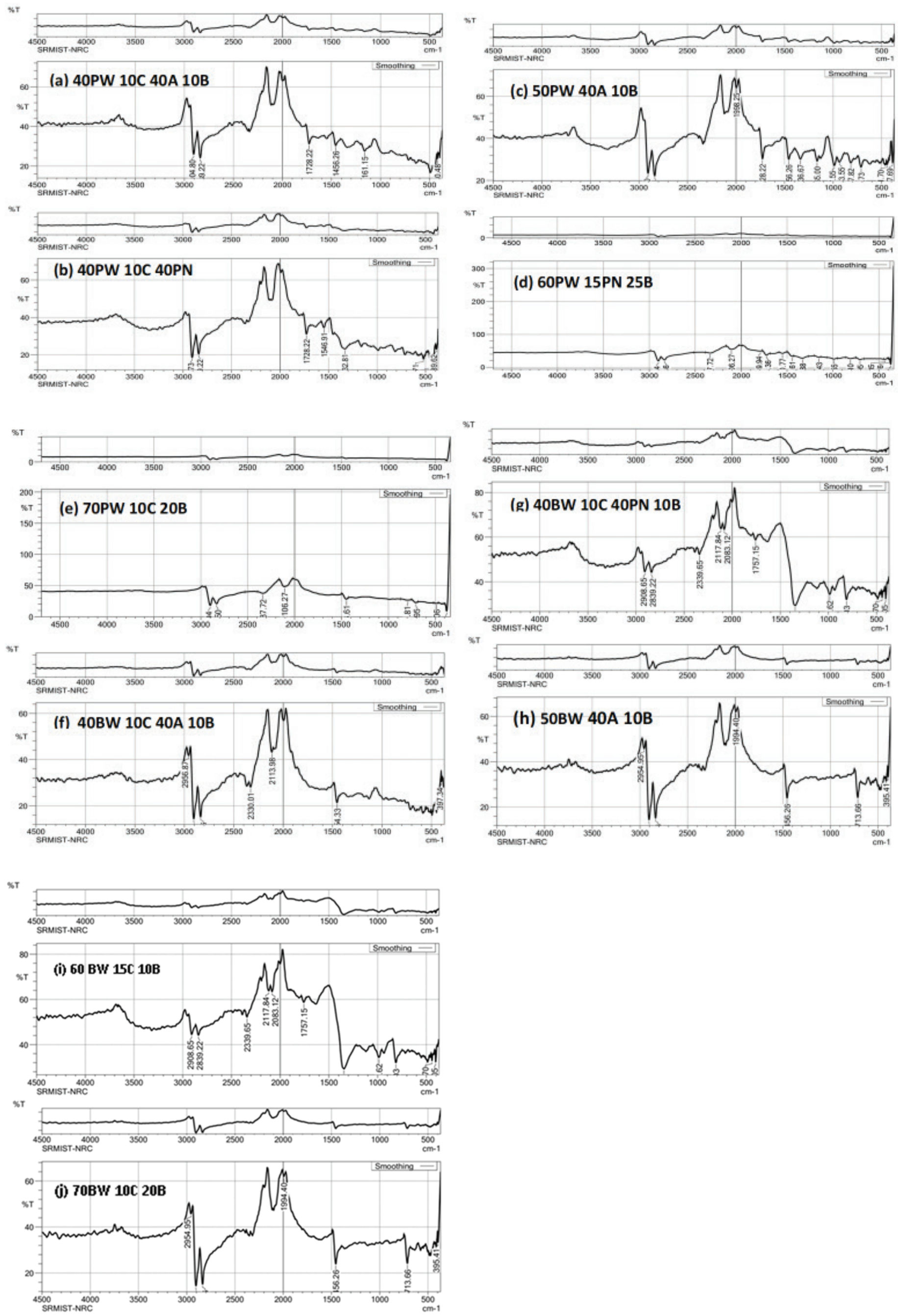


Figure 4. Fourier Transform Infrared (FTIR) spectroscopy spectra.

Table 5. Fourier Transform Infrared Spectroscopy Results

Fuel Sample	Peak Value
40BW10C40A10B	2956.87
40BW10C40PN10B	2908.65
50BW40A10B	2954.95
60BW15PN10B	3668.61
70BW10C20B	3668.61
40PW10C40A10B	2904.80
40PW10C40PN10B	2906.73
50PW40A10B	2904.80
60PW15PN25B	2900.94
70PW10C20B	2900.94

40BW10C40A10B and 50BW40A10B were almost similar but the bonding strength increased because of the addition of aluminum (Al) in them. [30, 31].

The fuel samples, 60BW15K10B and 10BW10C20B, recorded maximum values of 3668.61 indicating the base properties of beeswax can further optimize the binding power in the fuel. (Figure 4)

FTIR measures the absorption of infrared light from the molecular bonds. Different functional groups (C-H, C=O, O-H, etc.) have different absorption wavelengths. These values are plotted as an FTIR spectrum. For example:

- Peaks around 2900 cm^{-1} stretch C-H in long-chain hydrocarbons and allow efficient energy production during combustion.
- The strong O-H stretching causes the peak at a higher wavenumber (3668.61 cm^{-1}) in beeswax samples, so thermal stability improves.

The C-H and O-H groups cause higher combustion. They also cause specific impulse (Isp) properties. This makes beeswax a more suitable combustor fuel for hybrid rocket propellants. Although beeswax and paraffin wax are both composed of long-chain hydrocarbons, beeswax provides more stability to hybrid rocket propellants due to its superior molecular bonding and interactions. (Table 5)

Chemical groups such as alkanes, carbonyl and esters can be identified using FTIR to characterize the functional groups. The FTIR of beeswax identifies esters and fatty acids because their carbonyl peaks determine the physical and chemical properties of beeswax. The infrared spectrum of paraffin wax shows peaks corresponding to C-H stretching vibrations indicative of its simple hydrocarbon structure and the effect of its chemical composition on thermal stability and combustion.

SEM Analysis

Scanning electron microscopy has been used to study the paraffin wax morphology, and that of beeswax and other composition fuels. At ambient conditions, paraffin wax is solid at high molar mass. The wax is composed of crystalline platelets, while beeswax is liquid at room temperature and upon crystallization forms a much less dense material with smaller flakes.Based on SEM data, both waxes were found to have very similar elemental composition, dominated by carbon and oxygen. However, the paraffin composition (40PW10C40A10B) was more homogeneous than the beeswax composition (40BW10C40A10B) (Figure 5).

Under microscope analysis, paraffin wax is homogeneous with layers of different colors, but beeswax shows some topographical structure with a pasty, colloidal structure under high magnification. Due to a homogenous, evenly distributed structure, paraffin wax is thought to burn more uniformly than beeswax, which is less homogeneous. The irregular flakes produced in beeswax can cause localized hotspots and affect how clean it burns.

In SEM, a concentrated beam of electrons scans the surface of a material, and the emitted secondary electrons are detected to generate high-resolution images of the morphology of the surface of the specimen. This gives information about the homogeneity of the surface texture and the granulation. Such characteristics of the microstructure can also underline differences of waxes, such as paraffin (homogenous and smooth) and beeswax (multilayered, heterogeneous and with flakes). The morphology of the fuel also influences the mixing uniformity and the combustion efficiency.

It is also used to study the distribution of an additive such as aluminum or boron powder in a wax sample. In a sample of paraffin wax, a uniformly distributed additive may burn better, while beeswax samples tend to be not that homogeneous. This suggests that small homogeneities seen in the SEM images could be improved using chemical additives or advanced processing when samples are prepared with paraffin.

To explain these findings in the field, consider the following:

Combustion efficiencies and the thermal stability of the fuels are important values. For blended fuels, beeswax blends perform better than paraffin waxes because they present a 15% increase in the heat of fusion and a 10% increase in stability. Additives such as aluminium, boron and carbon have been used for both stabilizing regression rates, and stabilizing the fuel structure. In terms of analytical methods, Scanning Electron Microscopy can be used to study the mixing of the fuel as well as the particle distribution and interface structure of other porous rocket propellants. This is important to predict the behavior of engines in operation. XRD may also be used in quality control to analyze whether fuel samples' crystalline structures meet thermal stability requirements. FTIR (Fourier Transform Infrared Spectroscopy): Used to monitor chemical integrity and fuel degradation during storage.

Correlate Laboratory Results with Real-World Scenarios: Examine the advancements in regression rates concerning real-world rocket propulsion contexts, such as modest satellite launches, where improved fuel efficiency

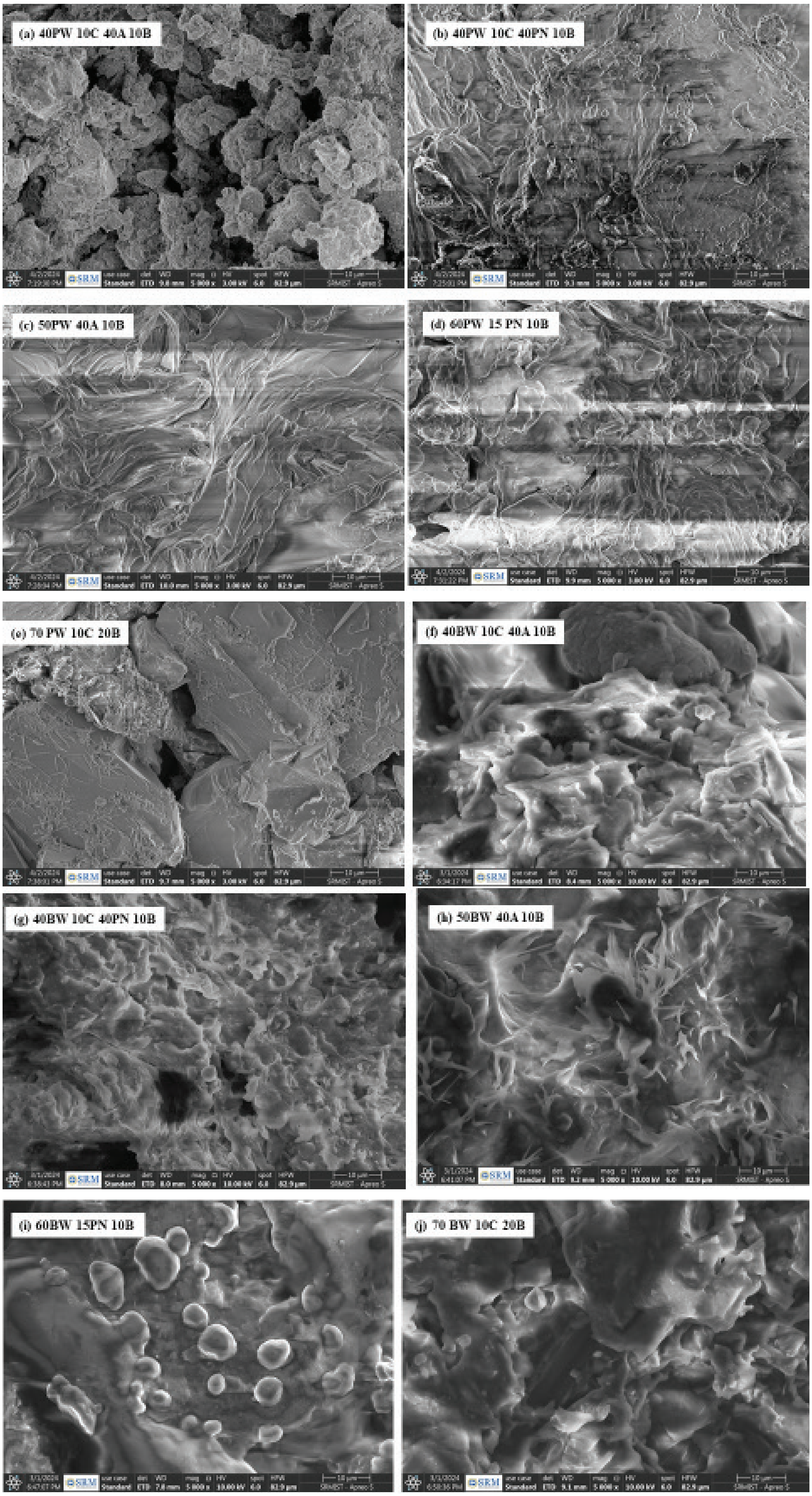


Figure 5. Scanning Electron Microscopy (SEM) Results.

might result in financial savings. Discuss the safety advantages, including the non-toxic and eco-friendly characteristics of the fuels, pertinent to instructional or low-impact space missions.

After the establishment of the field applications for these results:

Recommend incorporating these fuel samples into full-scale hybrid rocket engines to assess thrust, combustion efficiency, and performance in operational settings. Consider investigating alternative additions, including nanoparticles, to enhance regression rate and energy density. Perform lifecycle evaluations to measure ecological advantages, strengthening the argument for implementation in sustainable aerospace projects. Propose utilizing additive manufacturing to tailor fuel grain shapes, hence improving thrust profiles and efficiency for individual mission requirements. Such methods ease the transition from laboratory implementations of hybrid rocket technology to field applications of hybrid rocket technology.

The higher thermal stability and combustion performance of the fuels blended with beeswax further support what other researchers have reported. In terms of thermal stability and heat of fusion, the experimentally obtained values are 15% and 10% higher for the beeswax-blended fuels than the paraffins. This conforms to a work by Naoumov et al. [4], which shows that the use of bio-derived fuels (such as beeswax) and metallic additives can improve combustion performance, and another by Kim et al. [20] showing that adding polymers (such as LDPE) to paraffin also has an improving effect. The use of aluminum and boron additives also was shown to improve the regression rate and specific impulse (up to 12%). This is supported by the work of Karabeyoglu et al. [12] on improved regression rates of paraffin-fuels and the increase in performance compared to other solid propellants by the addition of metals, and of mechanical strengthening through the addition of EVA and activated charcoal demonstrated in your work and by Mahottamananda et al. [8], with EVA-beeswax blends exhibiting improved tensile strength and thermal resistance, further proving the efficacy of wax-based fuels as an environmentally-conscious, high performing fuel for hybrid rocket propulsion systems.

Keeping a blend of paraffin and beeswax in the right state can be difficult due to both these waxes melting at a low temperature. Paraffin becomes plastic at between 59 and 63 degrees Celsius. Beeswax melts at between 62 and 65 degrees Celsius. The structural integrity of these blends may degrade due to thermal cycling. This decline may cause handling difficulty and uneven combustion performance. These blends may become brittle and crack if stored and transported at very cold temperatures. The fuels are slowly oxidized by water and air, causing their constituents to change slightly and energy losses to occur. The least loss is achieved by storing the fuels in an air-sealed container at a stable temperature and in air with a low relative humidity. In addition to boiling point, wax-based fuels also have advantages over the conventional rocket propellant in being bio-derived, non-toxic and having lower quantities of hazardous waste as well as lower toxic emissions as burn products. We must consider by-products of the combustion process. Additives such as aluminum and boron can improve performance, but if burned underground, may produce fine particulates which are released and must be controlled to minimize their adverse effects on the environment. Inevitably, stored fuel can degrade and residuals can complicate disposal but, due to the low environmental impacts of wax-based fuels in comparison to other ingredients in some customary solid propellant formulations, they are an attractive choice of fuel within hybrid rocket propulsion systems.

CONCLUSION

SEM, XRD and FTIR can provide a lot of information. SEM could give us some information about surface microstructure that can help us to evaluate the overall homogeneity of fuel samples and how microstructure and surface texture are affecting combustion behavior (regression rates, stability of the combustion, etc.). XRD and the FTIR can be carried out for the analysis of the crystalline phases of the hybrid rocket fuel blends in different proportions and of the thermal and chemical stability of the additives dispersed in the wax matrix and can also help in finding out the type of bonding and functional groups across the blends and their thermal and chemical behavior.

The work characterizing the properties of these fuels forms the basis for producing safer, greener and more efficient hybrid rocket fuels. The work reported in this thesis examines the performance of hybrid rocket fuels using beeswax, paraffin wax and their mixtures as the solid fuel.

For the beeswax and paraffin wax (pure and mixtures), the XRD results show that the diffraction angle is not affected by the compositions and hence is consistent with the heterogenic blend structure. Thus the thermal properties of the blend such as specific heat, heat of fusion and melting point are mostly independent of the components. This conclusion is supported by the results of the SEM analysis. The FTIR spectra also showed that the blends were homogeneous. The bands corresponding to the maximum values were C-H stretching of alkanes, which are found in organic compounds.

The thesis contributes to the knowledge of paraffin wax, beeswax and some additives in hybrid rockets with respect to the environmental impact, mechanical properties and the thermal stability of this hybrid rocket propellant fuel. It adds to the knowledge of bio-derived fuels in hybrid rocket propulsion systems for the development of sustainable and efficient propellant fuels as alternatives to conventional solid fuels.

Future Scope

This work provided the first data for many of the bio-derived hybrid rocket fuels. Future work should include high fidelity combustion experimentation and engine testing to determine the regression rates, specific impulses, and combustion efficiencies of these bio-derived fuels. Improvement of thermal stability and energy density and fuel behavior with the use of optimized additives like metallic nanoparticles or functionalized materials would also have to be studied. The manufacturing process will need to be scaled up, and the fuels would need to be tested in a rocket, either sounding rockets or small satellite launch vehicles. Life cycle assessment and other studies of the environmental impact of the whole life cycle of fuels would be helpful in assessing the comparative benefits of hybrid propulsion versus other fuels. New methods such as the additive manufacture of ideal grain geometries and machine learning design have potential to revolutionize hybrid propulsion. The development of bio-sourced fuels could enable clean heating, low-power propulsion systems, and green weaponry. Partnering with aerospace agencies and institutions could help create validation and optimization sites for biofuels, and ultimately environmentally-friendly propulsion systems for many missions. Further research and testing will ultimately determine whether wax-based fuels can be considered practical as a hybrid rocket fuel. Field testing in rocket flight is necessary to understand the flight characteristics of rocket fuels, including a fuel's regression rate, combustion efficiency and in-flight performance. Full scale engines have been used to simulate the high pressure and temperature conditions within a rocket engine for testing specific fuels. The tests would determine the specific impulse of the fuels and their thermal and mechanical stability under the long exposures of flight conditions. The fuel must be qualified through environmental testing for temperature stability, stability under humidity conditions and altitude pressure change. Other parameters that need to be tested include stability tests on the waxes over long periods of time and their shelf life. Any degradation due to oxidation, moisture absorption etc., needs to be tested. Another test needs to be performed on post-combustion and a study of the resulting gases and particulates produced during combustion. Any resulting impact of the wax fuel on the environment due to emissions and combustion byproducts also needs to be studied. The above parameters need to be studied to ensure that wax based fuels are reliable, safe, and capable of performing effectively as hybrid rocket propulsion propellants. Future studies examining the structure of wax-based fuels prior to, and post, exposure to thermal tests or combustion tests may provide additional information about the performance of the fuel within its operating environment. The way the fuel matrix deforms, cracks, or shrinks during thermal or combustion tests will provide information about its mechanical properties. Studies of these structures could provide perception into the stabilizing (or destabilizing) effects of aluminum, boron, and carbon additives, and also possibly lead to optimum solid-fuel blends. Knowledge of ways in which the structure affects the stability of these fuel modifications may eventually permit reliability of the fuels, particularly under long-term and high-pressure storage conditions, to be improved, and perhaps development of a mechanical configuration that may be close to optimum, both from the mechanical instability standpoint and, possibly, from the energy usage standpoint, in an actual engine environment.

NOMENCLATURE

BW	Beeswax
DSC	Differential Scanning Calorimetry
EVA	Ethylene-Vinyl Acetate
HPRE	Hybrid Propellant Rocket Engine
HTPB	Hydroxide-Terminated polybutadiene
LDPE	Low Density Polyethylene
PE	Polyethylene
PW	Paraffin Wax
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction
FTIR	Fourier Transform Infrared Spectroscopy
OFB	Opposed Flow Burner
TGA	Thermo Gravimetric analysis
SFDR	Solid Fuel Ducted Rocket

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

Authors confirm that the data that supports the findings of this study are available within the article. The raw data that supports the findings of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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