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ORIGINAL ARTICLE

Characterization and performance analysis of eco-friendly solid rocket propellant from *Prunus armeniaca* L. agricultural residues

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Abstract

The increasing demand for sustainable energy solutions has prompted the aerospace industry to explore alternative fuels that minimize environmental impact. This study investigates the potential of utilizing apricot waste, a by-product of the agricultural sector, as a feedstock for solid rocket propellant (SRP) production. Through innovative conversion processes, including sulfurization and caramelization, apricot waste was transformed into a viable propellant. The resulting SRP exhibited favorable chemical properties, including a high calorific value of 1726 cal/g, indicating its potential for efficient energy release during combustion. Elemental analysis revealed a composition that is rich in oxygen, enhancing its eco-friendliness compared to traditional propellants. The moderate burn rate exponent ($n \approx 0.602$) suggests a balanced performance, making it suitable for applications requiring controlled thrust profiles. This research not only addresses the environmental challenges associated with conventional propellants but also highlights the importance of repurposing agricultural waste, thereby promoting sustainable resource utilization and waste reduction.

Keywords Agricultural waste · *Prunus armeniaca* L. waste · Green propellants · Solid rocket propellant (SRP) · Sustainable energy

Abbreviations

SRP	Solid rocket propellant
HHV	Higher heating value
LHV	Lower heating value
$KClO_3$	Potassium chlorate
Al	Aluminum
Fe_3O_4	Magnetite
r	Burning rate (m/s)
a	Burning rate coefficient (m/s * Pa^{-n} * K^{-m})
P	Chamber pressure (Pa)
T	Chamber temperature (K)
n	Pressure exponent
m	Temperature exponent
ΔT	Change of temperature (°C)
W	Water equivalent of the bomb (cal/°C)
w	Mass of the sample used (g)
e	Length of wire (cm)
t_1	Initial temperature (°C)
t_2	Final temperature (°C)
H	Hydrogen content of the propellant

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1 Introduction

The quest for sustainable energy solutions has become increasingly critical in the context of global environmental challenges and the need for alternative fuels in various sectors, including aerospace [1]. The aerospace industry, particularly, is exploring innovative approaches to reduce its carbon footprint and reliance on traditional fossil fuels [2, 3]. One promising avenue is the utilization of agricultural waste, specifically apricot waste, as a potential source for biofuels, including rocket propellants.

Apricot waste, which includes the pits and other by-products from apricot processing, represents a significant biomass resource that is often underutilized. The global production of apricots generates substantial amounts of waste, which, if not managed properly, can contribute to environmental pollution [4]. However, this waste can be transformed into valuable biofuels through various conversion processes, such as pyrolysis and fermentation, which

not only mitigate waste disposal issues but also contribute to the circular economy [5].

When considering biomass feedstocks, rice husks and palm kernel shells are among the most widely used and frequently mentioned in the literature. These materials have been extensively studied for their energy potential and applications in various sectors. Rice husks typically have a calorific value ranging from 14 to 16 MJ/kg [6], while palm kernel shells offer a slightly higher calorific value of 15 to 18 MJ/kg [7]. Both of these biomass types have established their viability as energy sources, particularly in combustion and gasification processes. In comparison, apricot waste presents a promising alternative with a calorific value ranging from 18 to 20 MJ/kg [7], making it a more energy-dense option than both rice husks and palm kernel shells. This superior energy density positions apricot waste as a potentially more efficient feedstock for applications such as solid rocket propellant, where high energy output is crucial.

Thermochemically, apricot waste exhibits superior thermal stability and optimal combustion characteristics, essential for efficient thrust generation in rocket propulsion. While rice husks and palm kernel shells have been widely utilized and researched, apricot waste remains underexplored despite its potential for a higher specific impulse and a lower environmental impact.

The combustion properties of rice husks and palm kernel shells have been well documented, showcasing their effectiveness as biomass feedstocks [8]. However, the unique characteristics of apricot waste, including its higher calorific value and favorable thermal stability, suggest that it could outperform these more commonly used materials in specific applications, particularly in the aerospace sector. Moreover, the utilization of apricot waste aligns with eco-friendly propellant development by reducing agricultural waste, thus promoting sustainability in both energy production and waste management. This underscores the need for further research into the application of apricot waste in solid rocket propulsion, as well as its broader implications for renewable energy solutions.

Recent studies have highlighted the potential of converting agricultural residues into biofuels, emphasizing the importance of developing sustainable and eco-friendly propellant solutions [9–11]. For instance, in their study, Osman et al. (2023) review various pathways for converting biomass into bioenergy and biochar, underscoring the significance of optimizing these pathways for energy production [12]. This research aligns with the exploration of apricot waste, which, with its calorific value ranging from 18 to 20 MJ/kg, presents a more energy-dense option than commonly used biomass feedstocks, such as rice husks and palm kernel shells. The superior thermal stability and optimal combustion characteristics of apricot waste make it a promising candidate for applications in rocket propulsion, where high energy output is crucial. By harnessing apricot waste for rocket fuel production, we can enhance energy security, reduce greenhouse gas emissions, and promote sustainability in both energy production and waste management.

In addition to environmental benefits, utilizing apricot waste for propellant production can enhance energy security by diversifying fuel sources and reducing dependence on imported fossil fuels. The integration of waste-to-energy technologies in the aerospace sector not only supports sustainability initiatives but also fosters innovation in fuel development. This paper will discuss the methodologies for converting apricot waste into rocket fuel, the challenges associated with this process, and the implications for future aerospace missions.

Aerospace propulsion can be made more sustainable by utilizing agricultural waste, such as apricot by-products, for bio-derived rocket fuels. While research has explored various organic waste materials, the potential of apricot waste in propulsion remains underexamined. This study addresses this gap by evaluating its combustion performance and viability as a sustainable propellant, contributing to environmental sustainability and energy security in the aerospace sector.

The exploration of alternative rocket propellants derived from organic wastes has gained traction in recent years, reflecting a growing interest in sustainable practices within the aerospace industry. This literature review synthesizes key findings from various studies that investigate the potential of organic waste materials as viable sources for rocket propellants.

One study focused on the development of alternative rocket fuels from household waste, particularly used cooking oils and agricultural residues like rice straw. This research aimed to create a cost-effective and efficient thrust mechanism for rocket technology, demonstrating the feasibility of utilizing organic waste as a fuel source [13]. The findings suggest that such alternative fuels could not only reduce reliance on traditional fossil fuels but also contribute to waste management solutions.

Another relevant study examined the combustion performance of solid biomass wastes, such as date stones and jojoba solid waste, in a hybrid rocket combustion chamber. The results indicated that these biomass fuels could generate thrust levels comparable to conventional hydrocarbon fuels, highlighting their potential application in propulsion systems [14]. This research underscores the importance of exploring diverse biomass sources to enhance the sustainability of rocket propulsion technologies.

Sackheim and Masse [15] explored green monopropellants as alternatives to hydrazine, noting significant advancements driven by commercial and government investments. Several candidates had completed or were nearing on-orbit demonstrations. The authors developed screening criteria

to compare their performance with traditional monopropellants, concluding that these green propellants offer promising solutions to hydrazine's toxicity and handling issues.

Aggarwal et al. [16] examined green propellants as alternatives to hydrazine, which poses environmental and health risks. Their review covered various green propellants, including ionic liquids, hydrogen peroxide, and biomass-derived fuels, comparing their performance to conventional options. While some green propellants did not yet match traditional performance, the authors noted ongoing advancements and stressed the need for further research to enhance the viability of these eco-friendly alternatives.

Pace et al. [17] presented the PulCheR project, which explored a pulsed chemical rocket using green high-performance propellants. Co-funded by the European Union, the project demonstrated a system that significantly reduced toxic emissions compared to traditional propulsion methods. By feeding propellants into the combustion chamber at low pressure and generating thrust through high-frequency pulses, the system improved performance while minimizing environmental impact. The study highlighted the potential of green propellants for environmentally friendly rocket technology in future aerospace applications.

Pandey and Bose [18] conducted a comprehensive review titled "Development of Green Propellants for Short Range Solid Rocket: an Overview." They emphasized the tactical applicability of solid propellants in short-range rockets, noting their advantages in terms of simplicity and quick deployment. The study highlighted the environmental and health hazards associated with traditional propellants, such as double-base and composite propellants, which produce smoky exhausts. The authors concluded that ongoing global efforts to develop green propellants could lead to safer and more environmentally friendly options for short-range rockets.

Florin-Marian Dîrloman et al. [13] examined the Mechanical Compression Behaviour of "Green" Rocket Propellants. They analyzed four new types of composite rocket propellants based on environmentally friendly oxidizers and metallic fuels. The study revealed that the mechanical properties of the propellants were significantly influenced by the binder composition and fuel granulation, leading to remarkable mechanical performances under compressive loads.

Barato [1] provided a Review of Alternative Sustainable Fuels for Hybrid Rocket Propulsion. This review discussed the potential of hybrid rockets using specific oxidizer-fuel combinations as a green alternative to traditional propulsion systems. The findings suggested that these hybrid systems could significantly reduce harmful emissions, making them a viable option for future rocket transportation.

A comprehensive review of existing literature reveals that, while several studies have investigated the use of agricultural waste for biofuel production, there is a notable gap in research specifically focusing on the application of these materials in rocket propulsion systems. Previous studies have primarily concentrated on the energy yield and combustion characteristics of agricultural residues, yet few have systematically compared the performance metrics of bio-derived propellants with traditional options. This study aims to fill this gap by not only analyzing the chemical composition of apricot waste but also by benchmarking its performance against established propellant standards, thus providing a clearer context for its viability as a sustainable alternative.

2 Materials and methods

This section outlines the materials and methods employed in the synthesis, characterization, and performance evaluation of a novel solid rocket propellant (SRP) derived from fresh apricot waste. The study utilized the widely cultivated apricot cultivar, *Prunus armeniaca* L., sourced from Hacihaliloglu farm in Malatya, Turkey. The methodology encompasses the collection and preparation of apricot waste, the selection of chemicals and equipment, and the detailed processes involved in the formulation of the SRP, including sulfurization, caramelization, and the preparation of oxidizers and catalysts.

2.1 Waste material collection

The study utilized the most commonly produced apricot cultivar, Prunus armeniaca L., in Turkey. Fully matured apricots were collected from Hacihaliloglu farm in July 2022, located in Ciftlik village, Malatya City, Turkey (geographical coordinates approximately 38°19′31″N, 38°28′11″E).

2.2 Chemicals and equipment

The following chemicals were used in the study:

Potassium chlorate ($KClO_3$) with a purity of 99% was purchased from Sigma-Aldrich (Istanbul, TR). Aluminum (15 µm particle size) with a purity of 98.50% and magnetite (5 µm particle size) with a purity of 96% were purchased from Nanokar-Nanotechnology (Istanbul, TR). 3-Carboxylic acid with a purity of 99% was purchased from Sigma-Aldrich (Istanbul, TR). Sulfur with a purity of 99.50% was purchased from Merck (Istanbul, TR).

The sulfurization process was conducted in an airtight room measuring 2.5 × 2.5 × 2.2 m (Fig. 1a). Trays made of perforated sheet metal (1 × 1 cm square holes) were used to stack the fresh apricots. The dimensions of the trays were 90 × 180 cm with a depth of 5 cm (Fig. 1b).

An automatic metal-edge filter (MAHLE AF 73S) was employed to filter the waste material. Dehumidification was performed using a lab oven (NUVE KD 200), while heating was conducted with an IKA C-MAG HS 7 heater. Mixing



(a) (b)

Fig. 1 **a** Airtight room setup for sulfurization process. **b** Trays for stacking fresh apricots (perforated sheet metal)

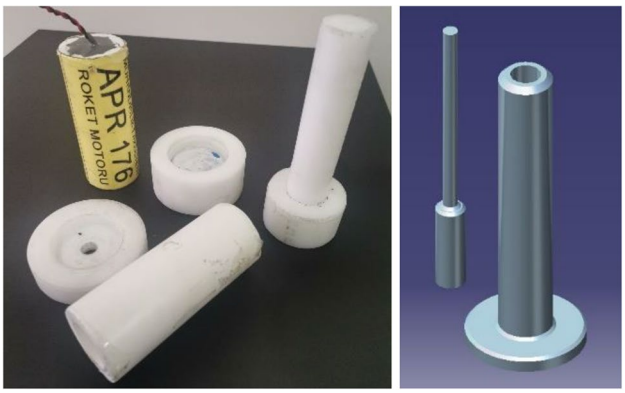


Fig. 2 Cylindrical molds for propellant photo and 3D design

was carried out using an ISOLAB light-duty mechanical stirrer (CN.615.01.001). Cylindrical molds were produced using PVC pipes with an outer diameter of 20 mm and an inner diameter of 10 mm (Fig. 2).

2.3 SRP preparation

2.3.1 Production of fuel

The apricots underwent a sulfurization pre-treatment. Approximately 1200 kg of fresh apricots (with seeds) were stacked in the tray within the airtight sulfurization room. A mixture of 2 kg of sulfur and 100 mL of ethyl alcohol (denatured alcohol) was prepared in a container and ignited inside the room. The airtight door was then closed to maintain the environment. This process was repeated every 24 h for 3 days, resulting in the complete sulfurization of the apricots. A viscous liquid, which flowed from the apricots, was collected on the floor of the room through the holes in the trays. This liquid formed the fuel used in the production of the SRP.

2.3.2 Caramelization process

The collected fuel was dried in an oven set at 105 °C until it reached a constant weight. The dried fuel was then placed in a steel reactor and heated to a temperature range of 160–188 °C. Continuous mixing was performed during the heating process until the raw material achieved a very dark shade of brown. This process involved a series of isomerization and polymerization steps characteristic of caramelization. These processes and their results are summarized in Table 1.

2.3.3 Preparation of catalysts and oxidizer

The oxidizer ($KClO_3$) and catalysts (Al and Fe_3O_4) were dehumidified in an oven set at 105 °C for 24 h. The oxidizer and catalysts were mixed in a weight ratio of 91:1:8, respectively, and ground to a size of 10 µm.

2.3.4 Mixing process

The prepared mixture of oxidizer and catalysts was added to the caramelized raw material in a weight ratio of 55:45. This mixture was then blended using a mechanical mixer until it became homogeneous. To enhance the final product's resistance to heat and humidity, 0.002 wt% citric acid was incorporated (Fig. 3).

Table 1 Different conversion processes used to transform apricot waste into propellant, including the conditions and outcomes of each process

Process	Description	Duration	Outcome
Sulfurization	Treatment with sulfur to enhance properties	3 days	Formation of viscous liquid fuel
Caramelization	Heating to achieve desired consistency	Variable (up to several hours)	Dark brown fuel
Mixing	Combining oxidizers and catalysts	Until homogeneous	Prepared propellant mixture



Fig. 3 Preparation process of the SRP

Table 2 Materials used in fuel production and their mass-to-weight ratios

Material	Ratio (%wt.)
Fuel (apricot waste)	44.6
Oxidizer ($KClO_3$)	50.3
Catalyst 1. (Al)	0.60
Catalyst 2. (Fe_3O_4)	4.30
Citric acid ($C_6H_8O_7$)	0.20

The materials used in fuel making and their mass-to-weight ratios are summarized in Table 2.

2.4 Characterization process

Elemental analysis quantified the composition of the propellant (CHNS- 932 model LECO). The calorific values of the propellant were determined using a bomb calorimeter (PARR 1341 plain jacket). Specific to the bomb calorimeter used in the experiment, the following formulas were used to calculate higher and lower heating values:

$$HHV = \frac{(\Delta T \times W) - (e \times 2.3)}{w} \quad (1)$$

$$LHV = HHV - 91.23H \quad (2)$$

where HHV is higher heating value (cal/g), LHV is lower heating value (cal/g), t_2 is final temperature (°C), t_1 is initial temperature (°C), ΔT is change of temperature (t_2-t_1) (°C), W is water equivalent of the bomb used, cal/°C, w is mass of the sample used (g), e is length of wire (cm), and H is the hydrogen content of the propellant.

Fourier transform infrared spectroscopy (FTIR) was employed to identify the functional groups present in the propellant, revealing the presence of carboxylic acids and other organic compounds (PERKIN ELMER 100 FTIR Spectrometer). X-ray diffraction (XRD) analysis determined the crystalline structure of the propellant (Rigaku RadB-DMAX II). Scanning electron microscopy (SEM) provided insights into the microstructural properties (LEO EV040).

2.5 Preparation of test samples and burning rate tests

The burning rate of the solid rocket propellant (SRP) was measured using cylindrical test samples with a diameter of 10 mm and a length of 100 mm. The samples were prepared by filling cylindrical molds with the propellant mixture, which had been compressed using a pusher piston. After molding, the samples (totally 20 pcs sample) were allowed to set for 24 h to ensure complete hardening.

The burning rate tests were performed in a controlled environment (Fig. 4) at a temperature of 300 K. Starting from the vacuum chamber pressure at atmospheric pressure, 20 test specimens were ignited in the chamber in such a way that one test was performed at every 5.05 kPa pressure drop. Each sample was ignited using an electronic ignition mechanism, and the combustion process was recorded using a high-speed camera. This allowed for precise measurement of the burning rate as the propellant burned.

The burning rate was determined by analyzing the recorded footage, which provided data on how quickly the surface of the propellant eroded as it combusted.

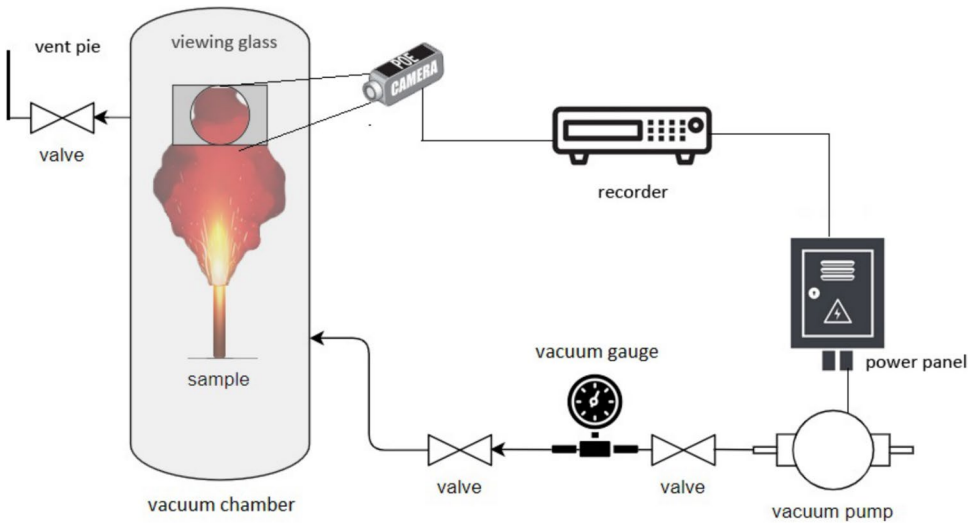


Fig. 4 Schematic representation of the experimental environment and setup

2.6 Pressure coefficient analysis

To further analyze the performance of the apricot waste propellant, a nonlinear regression analysis was performed on the burning rate data obtained from the tests. The relationship between the burning rate and chamber pressure was modeled using the following equation:

$$r = a \times P^n \times T^m \tag{3}$$

where r is the burning rate in meters per second (m/s), a is the burning rate coefficient in units of m/s * P^{-n} * K^{-m}, P is the chamber pressure in Pascal (Pa), T is the chamber temperature in Kelvin (K), n is the pressure exponent, m is the temperature exponent. Here because the data and analysis focus only on pressure, m will be neglected.

2.7 Computational tools/software

The calculations were performed using Minitab (version 17) for variance analyses and plotting the burning rate curve of SRP.

Design of SRP test molds and solid 3D models was carried out using CATIA (Version 5.21).

3 Results

3.1 Sulfurization process

The sulfurization process of fresh apricot fruit led to several chemical changes, including the formation of sulphites, inhibition of enzymatic browning, and osmotic dehydration, which collectively contributed to the production of a sticky sugary liquid. This liquid was rich in sugars and other soluble compounds, resulting from the breakdown of carbohydrates and the extraction of soluble solids during the treatment [19–21].

Due to its sugar composition, the sticky sugary liquid exhibited favorable combustion characteristics, making it a promising candidate for solid rocket propellant. During thermal decomposition, these sugars released significant energy and produced volatile intermediates that enhanced flame propagation and combustion efficiency. Additionally, caramelization at high temperatures further improved its energy output, reinforcing its viability as a sustainable alternative in propulsion applications.

3.2 Caramelization processes

This process involved a series of chemical transformations characteristic of caramelization, which was summarized in Table 3:

During the caramelization of sugars, particularly glucose and fructose, a series of chemical reactions occur, including dehydration, isomerization, and polymerization. These reactions lead to the formation of complex compounds that have higher energy densities compared to their original forms. The caramelization process results in the production of compounds such as hydroxymethylfurfural (HMF) and other oligomers, which are more energy-rich than simple sugars [22, 23]. Also, the breakdown of these complex sugars during combustion releases significant amounts of energy. The literature indicates that the combustion characteristics of these caramelized products are favorable, enhancing flame propagation and combustion efficiency, which is crucial for rocket propellant applications [24, 25].

Table 3 Chemical transformations during the caramelization process of sticky liquid from *Prunus armeniaca* L

Step	Description	Chemical Formula
1. Initial sugars	Primary sugars in fresh apricot fruit	Glucose: $C_6H_{12}O_6$ Fructose: $C_6H_{12}O_6$
2. Dehydration Reactions	Dehydration of glucose and fructose leading to reactive intermediates	Glucose: $C_6H_{12}O_6 \rightarrow C_6H_{10}O_5 + H_2O$ Fructose: $C_6H_{12}O_6 \rightarrow C_6H_{10}O_5 + H_2O$
3. Formation of HMF	Further dehydration forms Hydroxymethylfurfural (HMF)	$C_6H_{12}O_6 \rightarrow C_6H_6O_3 + 3H_2O$ HMF: $C_6H_6O_3$
4. Isomerization	HMF undergoes isomerization to form various isomers	$C_6H_6O_3 \rightarrow C_6H_6O_3$ (isomers)
5. Polymerization	HMF and intermediates polymerize to form complex caramel compounds	General Caramel Compound: $C_nH_mO_p$
6. Final products	Formation of caramel colorants and volatile compounds	Caramel Colorants: $C_nH_mO_p$

*Volatile compounds: various aldehydes, ketones, and acids

3.3 Effect of catalysts

The role of Fe_3O_4 (magnetite) and aluminum as catalysts in solid rocket propellants, focusing on their effects on ignition delay, burn rate, and flame stability. Fe_3O_4 enhances combustion efficiency by increasing reaction surface area, generating reactive oxygen species, and stabilizing the combustion process. Experimental results show a notable reduction in ignition delay due to its ability to lower activation energy, along with an improved burn rate critical for rocket thrust. Enhanced flame stability is evident from reduced pressure and temperature fluctuations, aligning with previous findings [26, 27].

A comparison with CeO_2 and TiO_2 (widely used in the literature for similar purposes) highlights Fe_3O_4's superior catalytic activity and thermal stability. While CeO_2 enhances combustion by oxidizing aluminum particles, it requires higher loading and has thermal stability issues. TiO_2, though a burn rate modifier, is less effective in reducing ignition delay and can cause agglomeration in propellant formulations. In contrast, Fe_3O_4 maintains high catalytic efficiency under extreme conditions due to its stability and reactive oxygen species generation [27, 28].

Aluminum also plays a key role in combustion, releasing energy upon oxidation. However, its reactivity can be hindered by an oxide layer, which Fe_3O_4 helps break down, enabling more efficient burning [29]. The combined effects of Fe_3O_4 and aluminum significantly improve ignition delay, burn rate, and flame stability, making them valuable in solid propellant formulations. Future research will focus on optimizing Fe_3O_4 loading and further investigating its catalytic mechanisms [26].

3.3.1 Characterization of the propellant

The characterization of the apricot waste propellant was conducted using various analytical techniques to assess its structural, thermal, and elemental properties. The following methods were utilized:

3.3.2 Elemental analysis

Elemental analysis was conducted to determine the composition of the propellant in terms of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). The results are given in Table 3.

The high oxygen content is particularly leading to eco-friendliness and a more sustainable combustion process. The low levels of nitrogen and sulfur contribute to the stability and safety of the propellant.

3.3.3 Calorific value determination

The calorific values of the propellant were determined using a bomb calorimeter. The higher heating value (HHV) was calculated to be 1726 cal/g, while the lower heating value (LHV) was found to be 1454 cal/g. These values are critical for assessing the energy output of the propellant during combustion and are indicative of its performance potential. In addition, calorific values obtained from the study were compared with the calorific values of non-green propellant types produced as a result of similar studies [30, 31]. Results showed that the produced SRP has a calorific value close to or higher than some of its counterparts (Table 4).

The calorific values of the various propellants (Table 5) reveal significant insights into their energy output potential.

Table 4 Elemental analysis results

Element	Percentage (%)
Carbon	15.13
Hydrogen	2.98
Nitrogen	0.03
Sulfur	0.38
Oxygen	81.48

Table 5 Average calorific values of different solid rocket propellants from literature and SRP produced as a result of the study (present SRP)

Propellant sample	Average calorific value (cal/g)	Reference
P0	1535	[30]
P1	1620	
P2	1586	
P3	1587	
Cordite	1394	[31]
SRP	1590 (± 0.30%)	SRP produced as a result of the study

*The designations P0, P1, P2, and P3 represent the fuel codes assigned to the various fuels discussed by the authors in their articles

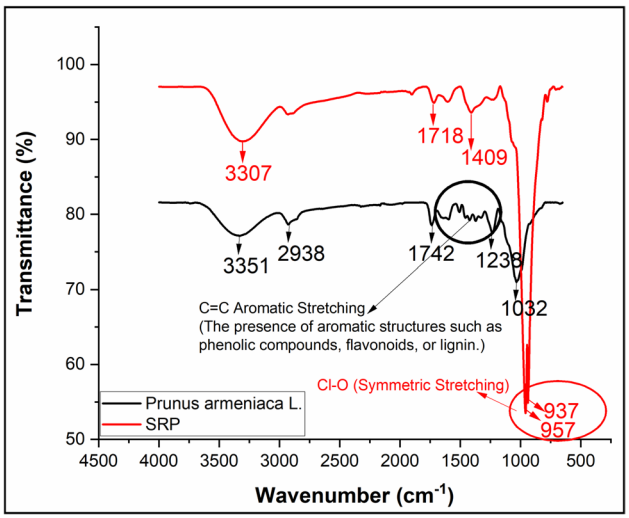


Fig. 5 FTIR results of SRP vs. *Prunus armeniaca* L

For P0, the calorific value is 1535 cal/g, which is lower than that of the solid rocket propellant (SRP) by 55 cal/g. In contrast, P1 exhibits a higher calorific value of 1620 cal/g, surpassing the SRP by 30 cal/g, suggesting a potentially better energy output during combustion. P2, with a calorific value of 1586 cal/g, is slightly lower than the SRP by 4 cal/g, indicating comparable performance. Similarly, P3 has a calorific value of 1587 cal/g, which is also marginally lower than the SRP by 3 cal/g, demonstrating that the SRP remains competitive in terms of energy output. Cordite, on the other hand, has a significantly lower calorific value of 1394 cal/g, falling short of the SRP by 196 cal/g, thereby highlighting the superior energy potential of the SRP. Overall, the calorific values of the SRP produced in this study, measured at 1590 cal/g, indicate its competitiveness with traditional solid rocket propellants (P0 to P3) and its marked advantage over Cordite. This analysis underscores the SRP's strong potential for effective energy output during combustion, positioning it as a viable alternative to existing propellant formulations and providing a clear context for its application in future propulsion systems. Further investigation into the combustion characteristics and efficiency of the SRP will be essential to fully elucidate its advantages over traditional propellants.

Additionally, the mean calorific value, standard deviation (SD), and standard error (SE) were calculated to analyze the energy content and variability of the propellant samples. A mean calorific value of 1542.4 cal/g was obtained, representing the average energy output. The standard deviation was found to be 86.6 cal/g, indicating moderate variation among samples, while the standard error of 38.7 cal/g suggested that the sample mean was a reliable estimate of the population mean. Calorific values ranged from 1394 cal/g (Cordite) to 1620 cal/g (P1), with Cordite identified as a potential outlier due to its significantly lower value. These findings are essential for performance prediction, as higher calorific values generally correspond to improved propulsion efficiency, while the standard deviation provides insights for quality control to ensure production consistency.

3.3.4 Fourier transform infrared spectroscopy (FTIR)

The FTIR spectrum reveals significant insights into the functional groups present within the SRP. Notably, the carboxylic acid functional group exhibits characteristics akin to both alcohols and ketones, as it encompasses both the O–H bond and the C = O bond. This results in a pronounced and broad absorption band spanning approximately 2800 to 3500 cm^{-1}, indicative of the O–H stretching vibrations. Concurrently, a distinct peak is observed in the mid-infrared region, specifically around 1710–1720 cm^{-1}, which corresponds to the C = O stretching vibrations.

The FTIR results (Fig. 5) indicate a broad band located at 3307 cm^{-1}, signifying the presence of the O–H bond, alongside a weaker peak at 1718 cm^{-1}, suggesting the existence of aldehydes and ketones within the fuel matrix. Additionally, a peak at 1409 cm^{-1} is indicative of C-H bending vibrations, while strong stretching vibrations at 937 cm^{-1} and 957 cm^{-1} further confirm the presence of C-H bonds associated with homo- and heteroaromatic compounds, as well as alkenes in the fuel composition. Apricot fruit and its industrial by-products contain various natural antioxidants, including flavonoids, phenolic acids, carotenoids, and lignin. Since these compounds possess aromatic or alkenic C = C double bonds, the observation of characteristic peaks in the FTIR spectrum is expected. In particular, the presence of β-carotene and other carotenoids, which contain conjugated double bonds, results in prominent C = C stretching vibrations in the FTIR spectrum. Furthermore, the analysis of the FTIR spectrum of SRP reveals peaks in the 950–1100 cm^{-1} wavelength range, corresponding to Cl–O stretching

vibrations. These bands indicate the symmetric and asymmetric Cl–O stretching vibrations of the chlorate ion.

3.3.5 X-ray diffraction (XRD)

The XRD pattern of the SRP, as depicted in Fig. 6, reveals several distinct reflections within the angular range of $2° < 2\theta < 8°$. The observed peak positions, ranging from approximately 1.41 to 4.37 Å, suggest a high degree of crystallinity, as evidenced by the sharp and symmetrical nature of the peaks.

Particularly, the sharp peaks at 30°, 35°, 43°, 57°, and 62° (2θ) are attributed to the crystalline phase of magnetite, as supported by previous studies [32]. Furthermore, crystalline peaks located around 39° and 65° (2θ) indicate the presence of aluminum within the fuel structure [33]. Notably, a rightward shift in the position of the XRD peaks may be associated with variations in the density and internal spacing of the crystalline structure. The presence of peaks at 26° ($d=$ 3.43), 27° ($d=3.32$), 31° ($d=2.95$), 32° ($d=2.87$), 34° ($d=$ 2.85), 47° ($d=1.91$), 51° ($d=1.77$), and 53° ($d=1.71$) (2θ) further corroborates this observation, potentially resulting from Van der Waals forces, intermolecular hydrogen bonding, or π-bonding interactions [34].

3.3.6 Scanning electron microscopy (SEM)

To elucidate the microstructural characteristics of the produced fuel, high-resolution scanning electron microscopy (SEM) was utilized. The SEM images, captured from the outer surface of the fuel (Fig. 7), reveal a heterogeneous structure with predominantly non-porous features. At a magnification of 2.50 K, the presence of magnetite particles is discernible on the surface, alongside aluminum particles exhibiting irregular and nodular morphologies.

3.3.7 Burning rate tests results

The analysis of the recorded footage provided data on the rate at which the surface of the propellant eroded during

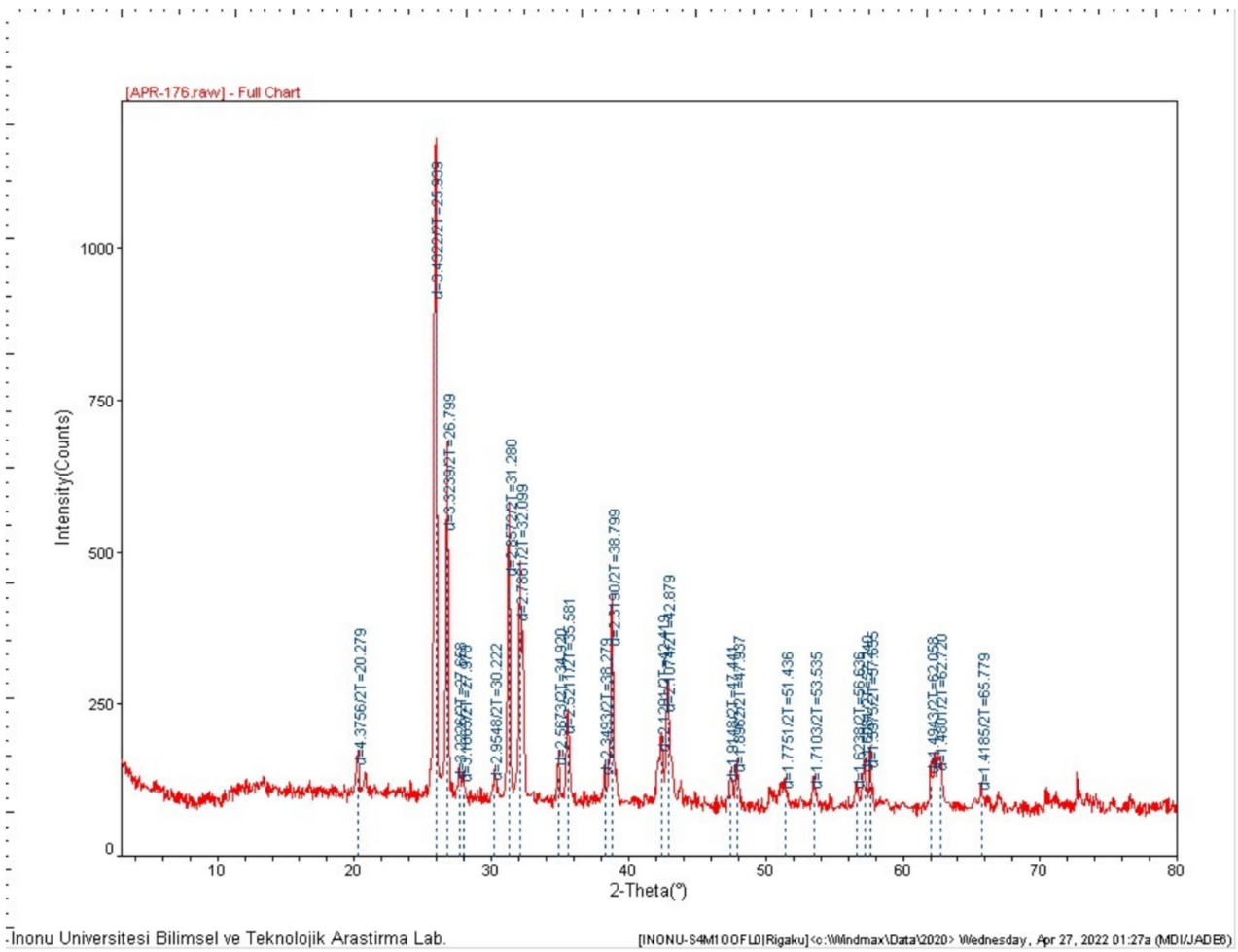


Fig. 6 XRD results of SRP

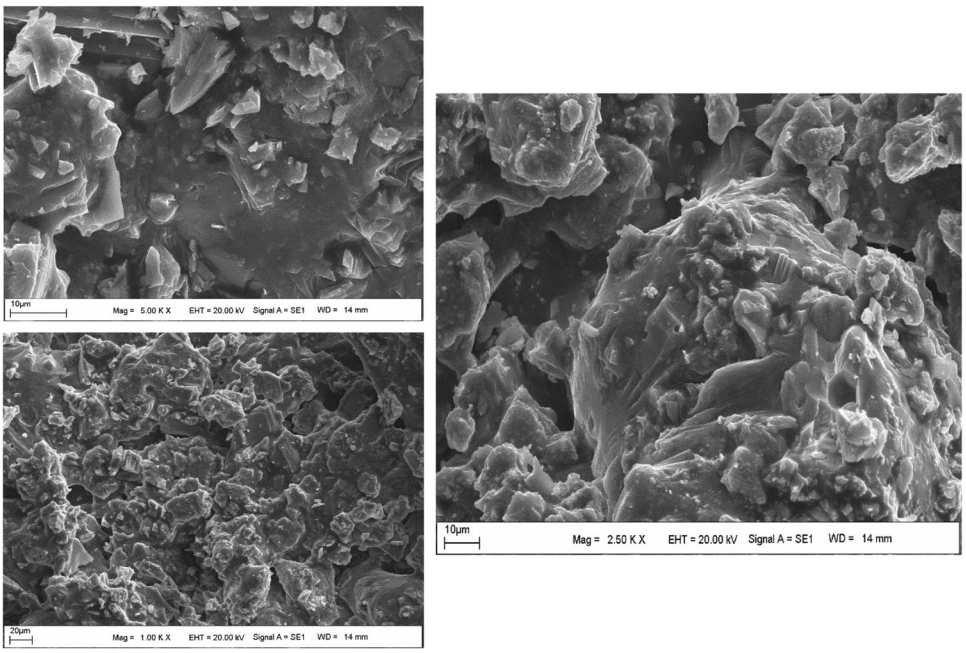


Fig. 7 SEM images of SRP with different magnifications

combustion. The results indicated that the burning rates varied with changes in chamber pressure. The outputs obtained from the burning rate test results are visualized in Fig. 8.

3.3.8 Pressure coefficient analysis results

According to Formula (3), the calculated burning rate equation for propellant is:

$$r = 0.067 \times P^{0.602}$$

as indicated by the formula, the burn rate exponent is approximately 0.602, and the coefficient a is roughly 0.067.

4 Discussion

The investigation into sustainable propellant solutions, specifically the conversion of apricot waste into rocket fuel, represents a significant step towards addressing the environmental challenges associated with traditional propellants. The results of the study demonstrate that apricot waste can be effectively transformed into a viable rocket propellant, showcasing not only the feasibility of utilizing agricultural by-products but also the potential for reducing waste in the food industry. This aligns with the growing trend in aerospace towards greener alternatives, as highlighted in recent literature.

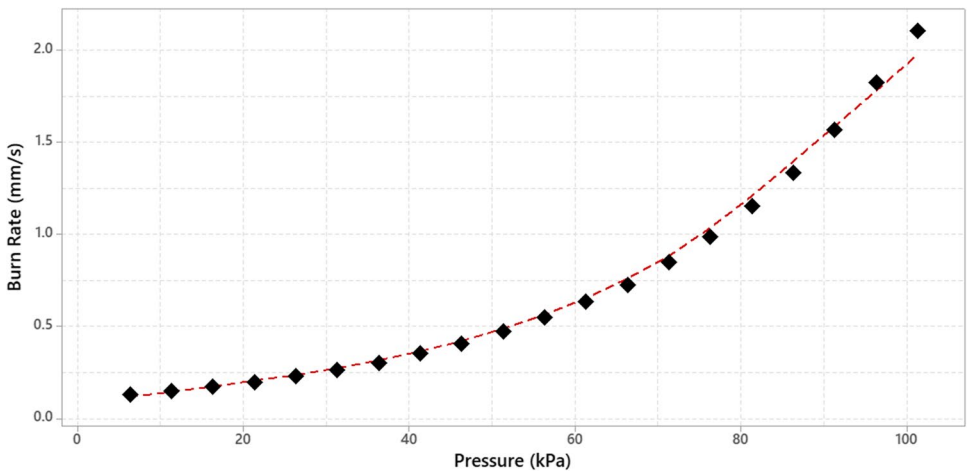


Fig. 8 Burning rate curve of SRP at sub-atmospheric pressures

4.1 Burn rate characteristics

The burn rate exponent $n \approx 0.602$ observed in the eco-friendly apricot waste propellant indicates a moderate increase in burn rate with pressure, which is beneficial for maintaining stable combustion in rocket engines. This behavior aligns with findings from other studies, such as those by Oatman et al. (2024), who investigated the behavior of various solid rocket propellants and reported similar trends in burn rate responses to pressure changes [35]. In contrast, conventional ammonium perchlorate (AP)-based propellants typically exhibit burn rate exponents that can vary significantly based on their formulation, often ranging from about 0.5 to 1.5. For instance, lower exponents ($n < 1$) indicate that the burn rate increases at a slower rate than the increase in pressure, which is often desirable for stability in rocket engines. Conversely, higher exponents ($n > 1$) suggest a more aggressive burn rate increase with pressure, potentially leading to instability and safety concerns, as noted by Shankar et al. (2019) [36].

The moderate exponent of the apricot waste propellant suggests a balanced performance, making it suitable for applications requiring controlled thrust profiles. This is particularly relevant when considering the pressure sensitivity of solid propellants, where the burn rate generally increases with pressure. The eco-friendly propellant's burn rate exponent of 0.602 implies that it will exhibit a moderate increase in burn rate with increasing pressure, contrasting with AP-based propellants that can show more pronounced changes, especially those with higher burn rate exponents.

Temperature sensitivity is another critical factor influencing the burn rate of solid propellants. As temperature increases, the burn rate typically rises due to enhanced thermal energy available for combustion [37]. The specific temperature sensitivity of the apricot waste propellant would need to be characterized through experimental testing, as it can vary based on the chemical composition and physical properties of the propellant. In realistic engine conditions, factors such as combustion chamber pressure, temperature, and the flow dynamics of the propellant will significantly influence the burn rate. Therefore, the performance of the eco-friendly propellant under these conditions would need to be validated through engine tests to ensure that it meets the required performance metrics for stability and efficiency.

The investigation into sustainable propellant solutions, specifically the conversion of apricot waste into rocket fuel, represents a significant step towards addressing the environmental challenges associated with traditional propellants. The results of the study demonstrate that apricot waste can be effectively transformed into a viable rocket propellant, showcasing not only the feasibility of utilizing agricultural by-products but also the potential for reducing waste in the food industry. This aligns with the growing trend in aerospace towards greener alternatives, as highlighted in recent literature [38, 39]. In contrast to some conventional propellants that exhibit higher burn rate exponents, often exceeding 0.8, which can lead to more aggressive combustion profiles, the balanced performance of the apricot waste propellant positions it as a promising candidate for future applications in sustainable rocketry.

4.2 Performance metrics

The burn rate results of the apricot waste propellant, particularly at higher pressures, suggest that it could be competitive with existing composite propellants. For instance, studies on ammonium nitrate-based propellants have shown varying burn rates depending on the formulation and additives used, as discussed by Xu et al. [38] and Oommen and Jain [40]. The current study's results indicate that the apricot waste propellant can achieve burn rates comparable to those of traditional formulations, which is a significant finding for its potential application in aerospace propulsion systems. The promising performance metrics of the apricot waste propellant underscore its viability as a sustainable alternative to traditional propellants. By demonstrating that agricultural by-products can be effectively transformed into high-performance propellants, this research not only highlights the potential for reducing waste in the food industry but also aligns with the aerospace industry's ongoing shift towards greener alternatives. These findings pave the way for further exploration into eco-friendly propulsion solutions that minimize environmental impact.

The investigation into apricot waste as a rocket propellant not only showcases its viability as an alternative to traditional propellants but also reflects the industry's shift towards sustainability. By transforming agricultural by-products into high-performance propellants, this research aligns with ongoing efforts to develop eco-friendly solutions, such as phase-stabilized ammonium nitrate and gel propulsion systems. This synergy highlights the potential for minimizing waste and prioritizing greener alternatives in aerospace propulsion.

Findings resonate with the increasing body of research focused on green propellants. For instance, Dîrloman et al. (2021) explored the use of phase-stabilized ammonium nitrate (PSAN) as an environmentally friendly oxidizer in composite solid propellants, emphasizing the need for alternatives to toxic oxidizers like ammonium perchlorate [41, 42]. Similarly, the study highlights the potential of apricot waste as a sustainable feedstock, contributing to the development of eco-friendly propellants that minimize environmental impact.

Moreover, the work of Kröger et al. [43] on gel propulsion systems illustrates the advantages of using gelled propellants, which combine the benefits of liquid and solid

propellants. Present research supports this notion by demonstrating that apricot waste can be processed into a gel-like consistency suitable for propulsion applications, thus enhancing safety and performance while reducing the ecological footprint.

The exploration of alternative propellants is further supported by Gotzig [44], who discusses the economic and environmental benefits of transitioning to green propellants for satellite propulsion. Findings in the present study contribute to this discourse by providing a practical example of how agricultural waste can be repurposed into a high-performance propellant, potentially reducing reliance on conventional, environmentally harmful options.

4.3 Considerations for further exploration

The successful conversion of apricot waste into rocket fuel opens avenues for further research into other agricultural by-products that could be similarly utilized. Future studies could focus on optimizing the conversion process to enhance yield and performance characteristics. Additionally, comparative analyses with other biofuels, such as those derived from algae or other fruit wastes, could provide insights into the most efficient and sustainable options available.

The integration of advanced technologies, such as machine learning and computational fluid dynamics, could also enhance the optimization of the conversion processes, leading to improved performance metrics for the resulting propellants. This aligns with the findings of Pace et al. [45], who emphasize the importance of innovative propulsion concepts that leverage green propellants [46].

4.4 Environmental impact

The use of apricot waste in propellant formulation offers several significant environmental benefits. Firstly, it reduces agricultural waste by repurposing by-products that would otherwise contribute to landfill and greenhouse gas emissions, promoting a circular economy. Secondly, the utilization of biomass-based materials in propellant production can contribute to a reduced environmental footprint, as renewable feedstocks help offset the reliance on non-renewable resources. Additionally, using apricot waste exemplifies sustainable resource utilization, decreasing reliance on toxic chemicals commonly found in conventional propellants. Preliminary calorific value assessments indicate that apricot-based propellants have the potential for competitive energy output, suggesting feasibility for practical applications. Overall, this innovative approach not only addresses the environmental challenges of propellant production but also aligns with broader sustainability goals in the aerospace industry.

4.5 Economic viability

The cost-effectiveness of producing propellant from apricot waste compared to conventional propellants is notable for several reasons. Firstly, apricot waste serves as a low-cost raw material, significantly reducing sourcing expenses compared to traditional propellants that rely on expensive, non-renewable resources like ammonium perchlorate. Secondly, the processing costs for apricot waste are likely lower due to simpler methods involved in its conversion, as opposed to the complex and hazardous processes required for conventional propellant production. Additionally, utilizing apricot waste can lead to economic benefits from waste reduction, as it transforms agricultural by-products into valuable resources, potentially lowering disposal costs and generating revenue. The performance of the apricot waste propellant, indicated by its calorific values, suggests it can compete effectively with traditional options, enhancing its market viability. Overall, the production of propellant from apricot waste is not only environmentally sustainable but also presents a cost-effective alternative to conventional propellants in the aerospace industry.

4.6 Life Cycle Assessment and techno-economic analysis

The increasing demand for sustainable energy solutions has prompted various industries, including aerospace, to explore alternative fuels that minimize environmental impact. In this context, the integration of Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) is crucial for evaluating the sustainability and economic viability of bioenergy production, particularly in the development of eco-friendly solid rocket propellants from agricultural apricot waste.

LCA is a comprehensive method that evaluates the environmental impacts associated with all stages of a product's life cycle, from raw material extraction to disposal [47, 48]. In the case of solid rocket propellant derived from *Prunus armeniaca* L. agricultural residues, LCA can help quantify the environmental benefits of repurposing agricultural waste. This study highlights that apricot waste, often discarded, can be transformed into a viable solid rocket propellant (SRP) through innovative processes, such as sulfurization and caramelization. This transformation not only reduces waste but also contributes to a circular economy by utilizing resources that would otherwise contribute to environmental pollution.

Techno-economic analysis (TEA) complements Life Cycle Assessment (LCA) by evaluating the economic feasibility of bioenergy production methods. In this context, the production of solid rocket propellant (SRP) from apricot (*Prunus armeniaca* L.) waste presents a cost-effective alternative to conventional propellants, which typically rely on expensive and non-renewable resources. The findings of this

study indicate that the calorific value of the produced SRP is comparable to or even higher than that of traditional propellants, highlighting its potential for efficient energy release during combustion. By utilizing low-cost agricultural by-products, the economic viability of eco-friendly propellant production is significantly enhanced, making it a promising option for aerospace applications.

The cost of solid rocket propellants varies considerably depending on factors such as composition, manufacturing processes, and market demand. Additionally, expenses related to manufacturing, handling, safety measures, and regulatory compliance further impact the final cost [49, 50]. For instance, previous studies have reported that a single kilogram of ammonium perchlorate composite propellant (APCP) can cost approximately 200 Yuan (around 35 USD) [51, 52]. A detailed cost analysis was conducted to determine the price per kilogram of SRP produced from apricot waste. Based on the data presented in Table 6, the cost of 1 kg of SRP derived from *Prunus armeniaca* L. agricultural waste is approximately 4.5 USD. This represents a sevenfold reduction in cost compared to the average market price of conventional SRP, reinforcing the economic advantage of utilizing agricultural waste as a raw material.

The integration of LCA and TEA provides a holistic view of the sustainability and economic potential of bioenergy systems. For instance, the environmental benefits of using apricot waste as a feedstock for SRP production, such as reduced greenhouse gas emissions and improved combustion efficiency, can be quantified through LCA. Simultaneously, TEA can demonstrate the cost savings associated with using agricultural residues, thereby supporting the case for investment in sustainable propellant technologies.

4.7 Industrial scalability and storage challenges

The methodology is industrially scalable. As with any production method, there will certainly be some losses and inefficiencies in the production of this product. However, the ease of the production processes and the fact that they are widely used in the industry (such as caramelization, sulfirization) and the small number of production stages will contribute to reducing these inefficiencies. The product will not have a problem of utilization, but storage will have a problem such as humidity. Storage conditions will need to be adjusted to minimum humidity conditions, which is already the case for rocket fuels and ammunition-like products.

4.8 Safety aspects

The apricot-based SRP demonstrates favorable thermal stability and a moderate burn rate exponent ($n \approx 0.602$), suggesting a balanced performance that may reduce the likelihood of aggressive combustion compared to traditional propellants, which often exhibit higher burn rate exponents and associated risks. While the high oxygen content of the apricot SRP enhances combustion efficiency and contributes to cleaner emissions, it also necessitates careful handling to mitigate reactivity. Furthermore, the degradation characteristics over time, influenced by the sugar content from the caramelization process, warrant further investigation to ensure long-term stability and safety. A comprehensive evaluation of these safety aspects, including ignition sensitivity and detonation limits, is recognized as essential for a holistic assessment of the apricot-based SRP's viability as a sustainable alternative to conventional propellants. Future research will focus on these critical safety parameters to enhance the understanding and application of this eco-friendly propellant.

5 Conclusion

The research presented in this study highlights the promising potential of utilizing apricot waste as a sustainable feedstock for rocket propellant production. The findings demonstrate that apricot waste, often discarded as an agricultural by-product, can be effectively transformed into a viable solid rocket propellant (SRP) through a series of innovative conversion processes, including sulfurization and caramelization. The characterization of the resulting

Table 6 Cost analysis table for SRP derived from *Prunus armeniaca* L. agricultural waste

Product	Price ($)	Composition per 1 kg of SRP (g)	Final Price ($)	Ref
Fuel (apricot waste)	0.5	446	0.223	
$KClO_3$	5.64	503	2.87	[53]
Al	32.7	6	0.19	[54]
Fe_3O_4	13.4	43	0.58	[53]
$C_6H_8O_7$	3.65	2	0.07	[55]
Sulphur	1.09	2	0.002	[56]
Production cost (per kg/$)			0.5	
Total price (per kg/$)			4.44	

propellant revealed favorable chemical properties, including a high calorific value, which indicates its potential for efficient energy release during combustion.

Furthermore, the moderate burn rate exponent observed in the propellant suggests a balanced performance, making it suitable for applications requiring controlled thrust profiles. This research not only addresses the environmental challenges associated with conventional propellants but also reflects a commitment to sustainability by repurposing agricultural waste, thus contributing to the circular economy. The economic viability of producing propellant from apricot waste further underscores its potential as a cost-effective alternative to traditional propellants, which often rely on expensive and non-renewable resources. Future research should focus on optimizing the conversion processes to enhance yield and performance characteristics, as well as exploring other agricultural by-products that could be similarly utilized. The integration of advanced technologies, such as machine learning and computational fluid dynamics, could also improve the efficiency of the conversion processes, leading to even better performance metrics for the resulting propellants.

In conclusion, the successful conversion of apricot waste into rocket fuel not only showcases its viability as an alternative to traditional propellants but also reflects the industry's commitment to sustainability. This innovative approach paves the way for further exploration into eco-friendly propulsion solutions that minimize environmental impact while maximizing performance. Future work on the eco-friendly solid rocket propellant derived from *Prunus armeniaca* L. agricultural residues will focus on several key optimizations. The propellant formulation will be refined by experimenting with different ratios of oxidizers and catalysts to enhance combustion efficiency and energy output. Additionally, alternative conversion methods will be explored to improve process efficiency, potentially reducing production time and costs, such as optimizing sulfurization and caramelization processes. Comprehensive performance testing will be conducted under varying operational conditions, including different chamber pressures and temperatures, to better understand the propellant's behavior in real-world applications. Advanced analytical techniques, such as computational modeling and machine learning, will also be integrated to predict performance outcomes and streamline the development of next-generation green propellants, significantly advancing sustainable aerospace technologies.

Author contribution Yeliz Toptas: investigation, data curation; Murat Toptas: writing—review and editing, writing—original draft, supervision, methodology, investigation, conceptualization.

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Data availability Data will be made available on request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI in the writing process During the preparation of this work, the author(s) used ChatGPT (a tool developed by OpenAI) in order to assist with correcting grammar mistakes and improving English writing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Yeliz Toptas has finished most parts of the experiments, wrote this paper. Murat Toptas finished parts of the experiments. Yeliz and Murat Toptas have provided the characterization experiments.

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