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Effect of Activated Carbon Addition on the Burning Rate and Energetic Characteristics of Sodium Nitrate–Sucrose Composite Solid Propellants

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Abstract— Composite solid propellants are widely used in rocket propulsion and gas-generating systems; however, many conventional formulations rely on chlorine-containing oxidizers that raise environmental concerns. This study evaluates a sodium nitrate–sucrose composite solid propellant and investigates the effect of activated carbon addition on combustion behavior and energetic characteristics. The propellant system consists of sodium nitrate as the oxidizer, sucrose as the fuel, unsaturated polyester resin as the binder, and activated carbon as a combustion-modifying additive. Two formulations, with and without activated carbon, were prepared to assess the influence of activated carbon on the composite system. The samples were characterized using visual inspection, linear burning-rate testing (n = 5), calorific value measurement by bomb calorimetry, Fourier Transform Infrared (FTIR) spectroscopy, and statistical analysis using Welch's t-test (α = 0.05). The formulation containing activated carbon exhibited a more controlled burning rate and showed a statistically significant difference compared with the formulation without activated carbon. The calorific value increased from 3338 - 4111 cal g^{-1}, equivalent to 13.908 – 17.129 kJ g^{-1}, while the calculated reaction enthalpy (−968 cal g^{-1}) confirmed the exothermic nature of the base sodium nitrate–sucrose system. FTIR analysis indicated the presence of characteristic functional groups and suggested possible interactions within the composite matrix, particularly involving oxygen-containing groups and activated carbon. These results indicate that activated carbon functions as a combustion-modifying additive that influences both burning rate and energetic characteristics. The findings represent a preliminary laboratory-scale evaluation of formulation effects in sodium nitrate–sucrose composite solid propellants.

Keywords— *Activated carbon; Burning rate; Calorific value; Composite solid propellant; Sodium nitrate–Sucrose*

1. INTRODUCTION

Solid composite propellants used in rocket propulsion are commonly formulated using perchlorate-based oxidizers, particularly ammonium perchlorate, which serves as the primary oxygen source and typically constitutes 60–90% of the total propellant composition [1–6]. In these systems, the oxidizer supplies oxygen to sustain combustion, while the fuel component generates high-temperature gaseous products responsible for thrust generation under confined conditions [7-8]. Although perchlorate-based propellants offer high performance and favorable mechanical properties, their combustion may produce chlorine-containing exhaust gases. These emissions are associated with environmental concerns, including atmospheric contamination, ozone depletion, acid rain formation, and smoke generation [9].

Nitrate-based compounds such as sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3), and ammonium nitrate (NH_4NO_3) have been investigated as alternative oxidizers because of their oxygen content, availability, and favorable thermal decomposition behavior [10]. Compared with perchlorate-based systems, nitrate-based formulations are of interest because they do not contain chlorine in the oxidizer structure; however, their combustion and energetic performance still depend strongly on formulation composition and fuel–oxidizer balance. Among these nitrate salts, sodium nitrate has received comparatively less attention in composite propellant systems, particularly in combination with sugar-based fuels, polymeric binders, and carbonaceous additives.

In composite solid propellant systems, the oxidizer must be combined with a suitable fuel to sustain redox combustion and generate energy. Nitrate salts, such as sodium nitrate and potassium nitrate, are commonly used as oxidizers because they have oxygen-rich compositions and suitable combustion characteristics. These oxidizers act as oxygen-supplying components,

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while sugar-based fuels provide carbon- and hydrogen-rich reducing species required for exothermic reactions [11].

Therefore, nitrate oxidizers are commonly combined with sugar-based fuels because such fuels are readily available, relatively low-cost, easy to process, and compatible with nitrate-based combustion systems. Various sugars, including sucrose, glucose, fructose, and sorbitol, have been reported as suitable fuels in nitrate-based propellant formulations [11].

Among these sugars, sucrose is frequently selected because it is widely available, relatively inexpensive, and capable of providing adequate energy output when combined with nitrate-based oxidizers. Sugar-based propellant systems have also been widely explored due to their simplicity, material accessibility, and suitability for experimental applications [12-13]. The compatibility between nitrate oxidizers and sugar-based fuels enables stable combustion through redox reactions, producing heat and gaseous products required for propulsion.

The combustion performance of solid propellants is characterized by their energetic properties and the stability of the combustion process. The burning rate is one of the most important parameters, as it directly reflects the rate of energy release and strongly influences combustion stability in rocket applications [14]. In addition, calorific value is widely used to represent the energetic characteristics of propellant systems due to its relatively simple measurement procedure and high accuracy. However, calorific value alone does not fully capture combustion behavior, particularly the burning rate, which is influenced by various physical, mechanical, and chemical factors. These variations highlight the importance of statistical analysis to ensure that representative and reliable burning rate data are obtained [15].

A previous study has reported that activated carbon can influence the burning rate in nitrate-based propellant systems compared to other additives [3]. The incorporation of carbonaceous materials may modify combustion behavior and reaction energy by enhancing fuel–oxidizer interactions and heat transfer within the system. These effects are strongly dependent on the physical properties of the carbon material used, such as surface area and porosity [9]. Considering that such material-dependent effects may introduce variability in burning-rate behavior, statistical evaluation is required to distinguish formulation effects from random experimental variation [16]. In this context, activated carbon is utilized in this study as an additive to further investigate its role in modifying combustion characteristics. Activated carbon can be derived from biomass-based precursors, which are widely available and commonly used in material applications [17]. However, most previous studies have primarily focused on basic combustion behavior or propulsion performance, whereas the combined evaluation of activated carbon effects on burning rate, calorific value, functional-group interactions, and statistical significance remains limited.

In composite solid propellant formulations, the binder plays a crucial role in maintaining structural integrity and ensuring proper interaction between the oxidizer, fuel, and additive components. Polymeric binders function to bind oxidizer and fuel particles into a cohesive structure while also contributing as a fuel during combustion [5]. In this study, polyester resin was selected as the binder to provide particle cohesion and mechanical stability within the composite system. In addition to its structural function, the binder can influence combustion behavior by affecting heat transfer and the distribution of reactive components. Polyester resin has been reported to maintain structural stability without significantly reducing combustion energy [10], making it suitable for laboratory-scale composite propellant preparation.

Considering the roles of the oxidizer, fuel, binder, and additive within the composite system, this study aims to evaluate the effect of activated carbon addition on the burning rate and energetic characteristics of sodium nitrate–sucrose composite solid propellants. Although nitrate–sugar propellant systems and carbon-based additives have been investigated in previous studies, limited attention has been given to sodium nitrate–sucrose formulations incorporating activated carbon within a polyester resin matrix, particularly with an integrated evaluation of burning behavior, energetic output, functional-group interactions, and statistical significance.

To address this gap, two sodium nitrate–sucrose composite formulations, with and without activated carbon, were prepared and compared. The combustion behavior was evaluated through linear burning-rate measurements, while the energetic characteristics were assessed using bomb calorimetry. Fourier-transform infrared (FTIR) spectroscopy was used to identify characteristic functional groups and to provide supporting evidence of possible interactions among the oxidizer, fuel, binder, and activated carbon within the composite matrix. In addition, Welch's t-test was applied to determine whether the observed differences in burning rate between the two formulations were statistically significant. Through this approach, the study provides a preliminary laboratory-scale assessment of how activated carbon influences the combustion and energetic performance of sodium nitrate–sucrose composite solid propellants.

2. EXPERIMENTAL SECTION

2.1. Materials

Sodium nitrate (analytical grade, 99.5% purity, Merck KGaA, Spain) was used as the oxidizer, and sucrose (analytical grade, 99% purity, Merck KGaA, Germany) served as the fuel. Activated carbon, with a surface area greater than 500 $m^2\ g^{-1}$ and a carbon content of approximately 80%, was employed as the additive. Unsaturated polyester resin (local supplier, Cimahi, Indonesia; density 1.1 $g\ cm^{-3}$) was used as the binder. Methyl ethyl ketone peroxide (local supplier, Cimahi, Indonesia) was used as the curing catalyst at 2 wt%

relative to the binder mass. All materials were selected based on commercial availability and suitability for composite propellant formulation. Unless otherwise stated, all chemicals were used as received without further pretreatment.

2.2. Instrumentations

Sample mixing was performed using an overhead stirrer (IKA RW 20) to ensure homogeneous dispersion of oxidizer, fuel, and additive materials within the binder matrix. Heating and continuous stirring during sample preparation were carried out using a hot plate and a magnetic stirrer (IKA RCT Basic) to facilitate binder melting and improve mixture uniformity. Calorific value measurements were conducted using a bomb calorimeter (IKA C2000 series) operated in accordance with ASTM D4809 to obtain reliable and reproducible energy content data [18]. Fourier-transform infrared (FTIR) spectra were recorded using a Shimadzu IR Prestige-21 FTIR spectrophotometer to identify characteristic functional groups and support the interpretation of possible component interactions within the composite matrix.

2.3. Preparation of Composite Solid Propellants

Composite solid propellant samples were prepared by weighing the raw materials according to predetermined formulations using an analytical balance with a readability of ±0.0001 g. For formulations without activated carbon, sodium nitrate and sucrose were mixed at a mass ratio of 50:50. For formulations containing activated carbon, sodium nitrate, sucrose, and activated carbon were mixed at a mass ratio of 40:40:20. These compositions were intentionally selected to represent fuel-rich conditions relative to the theoretical stoichiometric ratio of the sodium nitrate–sucrose reaction.

Unsaturated polyester resin was used as the binder at 42.31% of the total mixture for the formulation without activated carbon and 35.48% for the formulation containing activated carbon. All compositions were expressed on a mass-percentage basis. The addition of 20% activated carbon was intended to evaluate its influence on the combustion characteristics of the propellant system. However, this addition also altered the oxidizer–fuel balance; therefore, the observed combustion behavior was interpreted as the combined effect of activated carbon addition and formulation change.

The mixtures were homogenized using an overhead stirrer for 5 minutes. Subsequently, the mixtures were heated under continuous stirring. Unsaturated polyester resin was added as a binder, followed by the addition of methyl ethyl ketone peroxide catalyst at 2 wt% relative to the resin mass. The mixtures were stirred at 80 °C for 10 minutes until a uniform mass was obtained. The resulting mixtures were poured into molds with dimensions of 1 cm × 1 cm × 1 cm and cured for 24 hours to form solid composite propellant samples.

2.4. Burning Rate Test

Burning rate tests were conducted to evaluate the combustion behavior of the composite solid propellants. Each propellant sample was ignited at one end using an external flame source. The sample was positioned horizontally on a non-flammable holder to maintain consistent combustion conditions. The measurements were performed under ambient laboratory conditions at atmospheric pressure (1 atm) and room temperature (27 ± 2 °C). The combustion duration was recorded from the initial ignition until the flame reached the end of the sample. Time measurement was performed using a digital stopwatch with a resolution of 0.01 s. Each formulation was tested five times (n = 5) to ensure repeatability. The burning rate was calculated using **Eq. (1)**.

$$r = \frac{L}{\Delta t} \tag{1}$$

where r is the burning rate (cm s^{-1}), L is the burned length of the sample (cm), and Δt is the combustion duration (s). The obtained values represent surface burning rates under open-air conditions rather than combustion rates under confined motor conditions.

2.5. Statistical Analysis

A t-test was applied to evaluate whether a statistically significant difference existed between the burning rates of propellants with and without activated carbon addition. The hypotheses tested in this study were defined as follows: the null hypothesis (H_0) indicates that no significant difference exists between the two groups, and the alternative hypothesis (H_1) indicates that a significant difference exists between the two groups. In this study, Welch's t-test was applied to account for potential differences in variance and the small sample size. The t value was calculated using **Eq. (2)** [19]. where $\bar{x}_1$ and $\bar{x}_2$ represent the mean burning rates of the propellant without and with activated carbon addition, respectively; s_1^2 and s_2^2 denote the variances of each group; and n_1 and n_2 represent the number of samples in each group. The statistical analysis was conducted at a significance level of α = 0.05.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{2}$$

2.6. Calorific Value Test

The calorific value of the composite solid propellant samples was determined using a bomb calorimeter (IKA C2000 series) in accordance with ASTM D4809. Each propellant sample was combusted under controlled conditions, and the released heat was recorded by the calorimeter system. The results are reported in both calories per gram (cal g^{-1}) and kilojoules per gram (kJ

g^{-1}). This dual-unit reporting was used because calorie-based units are commonly found in energetic-material literature, whereas kJ g^{-1} provides SI-consistent reporting for thermodynamic interpretation. The use of both units also enables direct comparison with previously published propellant data and facilitates broader interpretation of energetic performance across different reporting conventions.

2.7. FT-IR Analysis

Fourier-transform infrared (FTIR) spectra were recorded using a Shimadzu IR Prestige-21 FTIR spectrophotometer in the range of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}. Each spectrum was obtained from 50 scans under ambient conditions. The samples were analyzed in solid form without further treatment. FTIR analysis was conducted to identify characteristic functional groups and to provide supporting evidence of possible interactions among the composite components.

2.8. Reaction Enthalpy Calculation

The reaction enthalpy was calculated based on the ideal stoichiometric combustion reaction of the sodium nitrate–sucrose propellant system. The calculation was performed as a theoretical approach under the assumption of complete combustion and the formation of stable reaction products. The ideal stoichiometric reaction used in this study is presented in **Eq. (3)**. The reaction enthalpy was determined using Hess's law under standard conditions of 25 °C and 1 atm, as expressed in **Eq. (4)**. where ΔH reaction represents the standard reaction enthalpy; v denotes the stoichiometric coefficient of each species; and $\Delta H_f°$ represents the standard enthalpy of formation of the reactants and products under standard conditions.

$$48NaNO_3(s) + 5C_{12}H_{22}O_{11}(s) \rightarrow 24Na_2CO_3(s) + 36CO_2(g) + 55H_2O(l) + 24N_2(g) \quad (3)$$

$$\Delta H_{\text{reaction}} = \sum v\Delta H_f^{\circ}{}_{\text{products}} - \sum v\Delta H_f^{\circ}{}_{\text{reactants}} \quad (4)$$

The calculation was carried out by subtracting the sum of the standard enthalpies of formation of the reactants from those of the products. The standard enthalpy of formation values employed in this calculation are summarized in **Table 1** [20]. This calculation was conducted to provide theoretical insight into the combustion energy potential of the investigated propellant system.

Table 1. Standard enthalpy of formation data

Compounds	Phase	$\Delta H°_f$ (kJ mol^{-1})
Sodium nitrate ($NaNO_3$)	s	−467.9
Sucrose ($C_{12}H_{22}O_{11}$)	s	−2221.0
Sodium carbonate (Na_2CO_3)	s	−1130.7
Carbon dioxide (CO_2)	g	−393.5
Water (H_2O)	l	−285.83
Nitrogen (N_2)	g	0

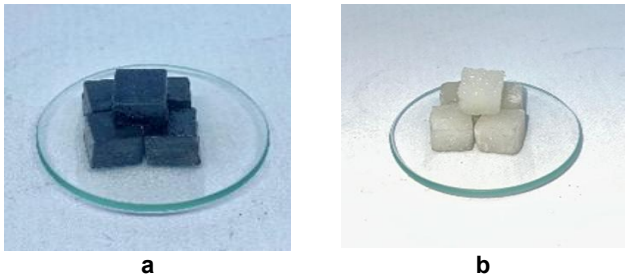
The enthalpy calculation was performed for the base sodium nitrate–sucrose system to provide a thermodynamic reference for the primary redox reaction. The reaction presented in Eq. (3) represents an idealized stoichiometric model and does not directly correspond to the experimental mass ratios used in this study, namely 50:50 for the formulation without activated carbon and 40:40:20 for the formulation containing activated carbon. In the experimental system, the presence of unsaturated polyester resin binder and activated carbon results in non-stoichiometric conditions, which may affect oxygen availability, combustion efficiency, and combustion pathways. Therefore, the calculated reaction enthalpy should be interpreted as an idealized thermodynamic reference rather than the actual heat release of the experimental formulations. The energetic contribution of activated carbon was evaluated experimentally through bomb calorimetry, as its effect is more appropriately represented by calorific-value data than by simplified stoichiometric modeling.

3. RESULT AND DISCUSSION

3.1. Physical Characteristics of Composite Solid Propellants

The physical characteristics of the prepared composite solid propellants were evaluated through qualitative macroscopic observation, focusing on sample shape, surface uniformity, color, and structural integrity. The sodium nitrate–sucrose composite solid propellants were successfully cast into cubic specimens (1 cm × 1 cm × 1 cm) and cured for 24 h, as described in Section 2.3. Both formulations exhibited sufficient mechanical integrity for handling and testing, indicating effective binding of the solid particles by the unsaturated polyester resin.

As shown in **Fig. 1**, the formulation containing activated carbon exhibited a darker appearance and a more visually homogeneous surface than the formulation without activated carbon. No macroscopic cracks, voids, or structural defects were observed, indicating that the mixing and curing procedures produced specimens suitable for subsequent linear burning-rate testing and calorimetric analysis.



a b

Fig. 1 Visual appearance of molded composite solid propellant specimens: (a) sodium nitrate–sucrose with activated carbon and (b) sodium nitrate–sucrose without activated carbon

However, this observation was limited to macroscopic evaluation and may not fully represent the internal structure of the composite. The observed differences in color and surface texture are likely associated with the presence and dispersion of activated carbon within the binder matrix, which may also indicate improved formulation homogeneity at the laboratory scale.

3.2. Burning Rate Characteristics

The burning rate was evaluated using the linear burning method described in Section 2.4., where one end of the specimen was ignited using an external flame and the burning rate was calculated as r=L/Δt. Each formulation was tested five times (n = 5), and the results are presented [16]. The burning rate data are summarized in **Table 2.**

Table 2. Burning rate of sodium nitrate–sucrose composite solid propellants (n = 5)

Propellant Composition	Burning Rate (mean ± SD) (cm s^{-1})
$NaNO_3$-$C_{12}H_{22}O_{11}$	0.0264 ± 0.00055
$NaNO_3$-$C_{12}H_{22}O_{11}$-C	0.0244 ± 0.00055

The formulation without activated carbon exhibited a higher mean burning rate than the formulation containing activated carbon. The low standard deviations in both cases indicate good repeatability across replicate tests and stable experimental conditions. Therefore, the observed difference in burning rate is mainly attributed to formulation differences rather than experimental uncertainty.

The combustion behavior of the composite propellant is governed by the combined effects of its constituent components, namely sodium nitrate as the oxidizer, sucrose as the fuel, polyester resin as the binder, and activated carbon as the additive. Sodium nitrate acts as the primary oxidizer, decomposing at elevated temperatures to release oxygen required for combustion, which directly influences fuel oxidation and the overall burning rate of the system [21].

Sucrose serves as the main fuel component, contributing to heat release and flame propagation through thermal decomposition, which generates combustible intermediates and gaseous products that sustain the combustion process. Therefore, the balance between oxidizer and fuel plays a crucial role in determining combustion efficiency and burning rate.

The polyester resin acts as a binder to maintain the homogeneity of the propellant mixture and improve its mechanical integrity. In addition, the binder contributes to more stable combustion behavior without significantly compromising the overall energy release of the propellant [10]. However, a relatively high binder content may reduce the burning rate by limiting direct contact between oxidizer and fuel particles and by acting as a thermal barrier within the composite matrix.

The reduction in burning rate upon activated carbon addition indicates that the carbonaceous additive influences combustion propagation in the propellant system [22]. Carbon materials have been reported to modify heat transfer and reaction pathways during combustion, which can reduce the propagation rate of the combustion front [23]. A similar reduction in burning rate has been associated with carbon additives that decrease thermal feedback from the flame to the propellant surface [24]. Collectively, these studies support the interpretation that carbon additives may function as burning-rate regulating agents rather than combustion accelerators, depending on their interaction with the oxidizer–fuel–binder matrix.

It should also be noted that the addition of 20% activated carbon significantly modifies the base formulation from 50:50 to 40:40:20, thereby altering the oxidizer–fuel balance. As a result, the observed decrease in burning rate is influenced not only by the presence of activated carbon but also by changes in the overall formulation. In the context of laboratory-scale screening, the decrease in burning rate suggests a shift toward more controlled combustion behavior, which is beneficial for achieving predictable and repeatable burning characteristics. This behavior also implies satisfactory formulation homogeneity, as uniform dispersion of oxidizer, fuel, and additive components contributes to stable flame propagation and minimizes irregular burning caused by localized compositional variations.

To position the present results within previously reported nitrate–sugar propellant systems, a comparison of burning rates is presented in **Table 3.**

Table 3. Comparison of burning rates of sugar-based composite propellants

Propellant System	Composition (wt%)	Additive	Burning rate (mm s^{-1})	Ref.
$NaNO_3$–Sucrose	50:50	None	0.264	This study
$NaNO_3$–Sucrose	40:40:20	Resin + AC	0.244	This study
KNO_3–Sucrose	65:35	None	9.6	[25]
KNO_3–Sucrose	65:32:3	Carbon	3.7	[25]
KNO_3–Sucrose	60:40	None	3.7	[3]
KNO_3–Sucrose	60:35:5	AC	2.89	[3]

AC = activated carbon. The $NaNO_3$–sucrose data were obtained from the present study, whereas the KNO_3–sucrose data were taken from previous reports.

As shown in **Table 3**, the burning rate of the sodium nitrate–sucrose propellant developed in this study was lower than those reported for potassium nitrate–sucrose propellants, which ranged from 2.89 to 9.6 mm s^{-1} [3,25]. This difference may be attributed to variations in oxidizer type, formulation composition, binder content, and additive effects.

The effect of carbon-based additives on burning rate has been reported to be system-dependent. Adeniyi et al. [25] observed a significant decrease in burning rate with carbon addition, whereas Bharti et al. [3] reported different effects depending on additive type and concentration. In the present study, the incorporation of activated carbon resulted in a decrease in burning rate

from 0.264 to 0.244 mm s^{-1}, indicating its role as a combustion-modifying additive.

The lower burning rate observed in this study indicates more controlled combustion behavior under open-air laboratory conditions. Although the comparison involves KNO_3-based systems, it remains relevant because both systems belong to nitrate-based sugar propellants with similar general combustion mechanisms.

3.3. Statistical Analysis of Burning Rate

An independent two-sample t-test (Welch's t-test) was applied to determine whether the burning rate differed significantly between formulations. The analysis was conducted at a significance level of $\alpha = 0.05$. The assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene's tests, respectively. The normality assumption was not satisfied ($p < 0.05$), while the homogeneity of variance was met ($p > 0.05$). Therefore, Welch's t-test was used as a more robust approach.

Table 4. Statistical summary of burning-rate comparison using Welch's t-test [26]

Parameter	Without Activated Carbon	With Activated Carbon	Statistical Value
Mean, $\bar{x}$ (cm s^{-1})	0.0264	0.0244	—
Standard deviation, s (cm s^{-1})	0.00055	0.00055	—
Sample size, n	5	5	—
Mean difference, ($\bar{x}_1 - \bar{x}_2$) (cm s^{-1})	—	—	0.0020
Standard error, SE (cm s^{-1})	—	—	0.000348
t-value	—	—	5.75
Degrees of freedom, df	—	—	8
p-value (two-tailed)	—	—	0.0004
95% confidence interval for mean difference (cm s^{-1})	—	—	0.00120–0.00280
Significance (α = 0.05)	—	—	Significant

Since $p < 0.05$, the null hypothesis (H_0) was rejected, indicating that activated carbon addition significantly affected the burning rate of the investigated sodium nitrate–sucrose propellant system under the experimental conditions. Although the normality assumption was not fully satisfied, Welch's t-test provides a more robust comparison for small datasets and potential variance-related limitations.

Statistical validation strengthens the interpretation of combustion data, as burning-rate measurements inherently exhibit variability and require objective evaluation to distinguish formulation effects from random variation [16]. Consequently, the results indicate that activated carbon addition produced a measurable and statistically significant reduction in burning rate under the test conditions.

3.4. Calorific Value and Energy Characteristics

The calorific value of the samples was determined using a bomb calorimeter (IKA C2000 series) in accordance with ASTM D4809, as described in Section 2.8. The results are presented in **Table 5**.

Table 5. Calorific value of sodium nitrate–sucrose solid composite propellant

Propellant Composition	Calorific Value (cal g^{-1})	Calorific Value (kJ g^{-1})
$NaNO_3$-$C_{12}H_{22}O_{11}$	3338	13.908
$NaNO_3$-$C_{12}H_{22}O_{11}$-C	4111	17.129

The formulation containing activated carbon exhibited a higher calorific value than the formulation without activated carbon. This increase indicates enhanced heat release during combustion, suggesting that the additive contributes to the energetic output of the composite. Importantly, this energetic enhancement occurred concurrently with a reduction in burning rate, implying that activated carbon influences combustion behavior by modifying energy release characteristics and combustion propagation dynamics rather than simply accelerating reaction kinetics.

To further support the experimental findings, a theoretical reaction enthalpy calculation based on the ideal stoichiometric sodium nitrate–sucrose system was conducted as a thermodynamic reference, as described in Section 2.8. The calculated enthalpy values are summarized in **Table 6**.

Table 6. Theoretical combustion reaction enthalpy of the sodium nitrate–sucrose system

Parameter	Value
$\Delta H_{reaction}$	−968 cal g^{-1}
Reaction Characteristics	Exothermic

The negative ΔHreaction confirms the exothermic nature of the base redox reaction. Although this stoichiometric calculation does not represent the experimental mass ratios, it provides a consistent thermodynamic baseline for interpreting the energetic potential of the sodium nitrate–sucrose system. Calorific value and reaction enthalpy represent complementary energetic descriptors: calorific value reflects experimentally measured heat release, whereas reaction enthalpy provides a theoretical estimate based on standard formation data. The combined use of both parameters is appropriate for preliminary energetic evaluation at the laboratory scale prior to advanced propulsion-level testing.

The theoretical stoichiometric ratio of the sodium nitrate–sucrose reaction corresponds to approximately 70.47% $NaNO_3$ and 29.53% sucrose by mass. In contrast, the experimental formulations used in this study, namely 50:50 and 40:40:20, differ from this ideal ratio and therefore represent fuel-rich mixtures. This indicates that the theoretical enthalpy was calculated under ideal stoichiometric conditions, whereas the experimental system operated under non-stoichiometric conditions.

Therefore, the theoretical value does not directly represent the actual heat release of the experimental formulations, but serves as a reference for

understanding the energy potential of the sodium nitrate–sucrose system. The difference between theoretical and experimental results may be attributed to formulation composition, oxygen imbalance, incomplete combustion, and the presence of additional components such as the polyester resin binder and activated carbon.

3.5. Combustion Mechanism

To further interpret the observed combustion behavior, the sodium nitrate–sucrose composite propellant can be considered as a redox-based system, in which sodium nitrate acts as the oxidizing component, while sucrose and the organic binder contribute as fuel-rich components. Upon heating, sodium nitrate may decompose and provide oxygen-containing species that promote the oxidation of carbon- and hydrogen-rich components. These reactions can generate gaseous products such as CO_2, CO, and H_2O, accompanied by heat release.

The presence of unsaturated polyester resin introduces additional hydrocarbon content into the composite matrix, which may also participate in the combustion process and influence energy release, heat transfer, and flame propagation. Meanwhile, activated carbon may modify combustion pathways by affecting thermal feedback, heat distribution, and heterogeneous reactions within the propellant matrix. These effects are consistent with the observed decrease in burning rate and increase in calorific value, suggesting that activated carbon influences both combustion propagation and energy-release behavior.

3.6. FTIR Analysis

As shown in **Fig. 2,** shows the FTIR spectra of sodium nitrate–sucrose composite solid propellants with and without activated carbon. FTIR analysis was conducted to identify the main functional groups present in the composite matrix and to evaluate possible interactions among sodium nitrate, sucrose, polyester resin, and activated carbon. In this study, the FTIR spectra were compared between the composite formulation containing activated carbon and the composite formulation without activated carbon. Therefore, the interpretation is presented cautiously as supporting evidence of functional-group interactions within the composite matrix, rather than definitive proof of the formation of a new covalent compound.

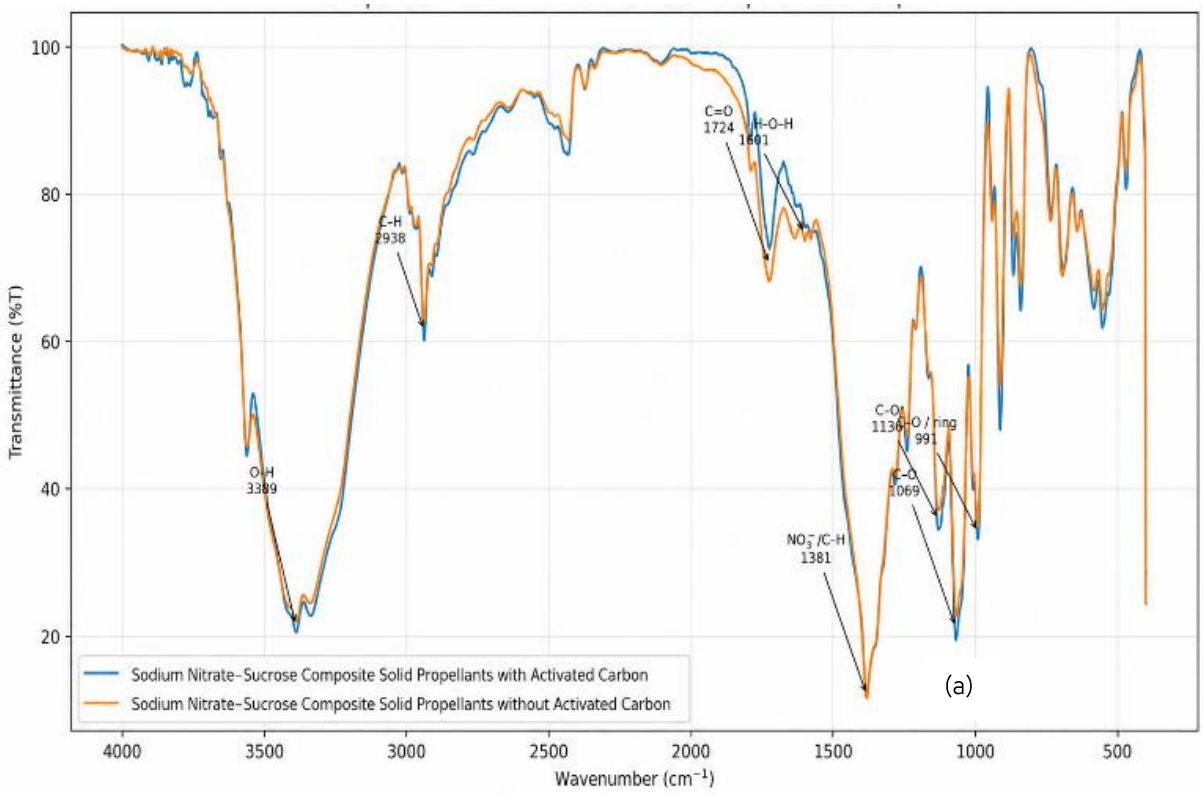


Figure 2. FTIR spectra of sodium nitrate–sucrose composite solid propellants with and without activated carbon, showing the main absorption bands associated with O–H, C–H, C=O, NO_3^-, and C–O/C–O–C vibrations

The main FTIR absorption bands are summarized in **Table 7**. Both samples showed similar characteristic absorption bands, indicating that the formulations possessed the same basic sodium nitrate–sucrose–polyester resin composite matrix. However, differences in band intensity, particularly in the O–H, C=O, and C–O/C–O–C regions, suggest that activated carbon may influence the interaction and distribution of oxygen-containing functional groups within the composite matrix.

The broad absorption band at 3336–3389 cm^{-1} is attributed to O–H stretching vibrations, which may originate from hydroxyl groups in sucrose, adsorbed moisture, and oxygen-containing groups on the activated carbon surface. The absorption band at 2937

cm^{-1} corresponds to aliphatic C–H stretching, indicating the presence of organic components from sucrose and the polyester resin binder. A distinct band at 1724 cm^{-1} is assigned to C=O stretching, which is commonly associated with ester carbonyl groups from the polyester resin binder.

The strong absorption band at 1381 cm^{-1} is associated with nitrate-related vibrations from sodium nitrate and may also overlap with C–H bending vibrations in the organic components. Several bands in the fingerprint region, particularly at 1240, 1130, 1068, and 991 cm^{-1}, are attributed to C–O and C–O–C stretching vibrations from sucrose and the polyester resin binder. These spectral changes support the role of activated carbon as a combustion-modifying additive that may affect intermolecular and surface interactions within the composite matrix.

Nevertheless, because the present FTIR data focus only on the prepared composite samples, further comparison with individual raw materials is recommended to provide more detailed component-specific confirmation. Thus, the FTIR results should be interpreted as supporting evidence of functional-group interactions rather than definitive proof of the formation of a new covalent compound.

Table 7. FTIR band assignment of sodium nitrate–sucrose composite solid propellants

Wavenumber (cm^{-1})	With AC / Without AC (%T)	Functional group assignment	Interpretation
3336–3389	22.687–20.476 / 24.421–22.047	O–H stretching	Indicates hydroxyl groups from sucrose, adsorbed moisture, and possible oxygen-containing groups on activated carbon.
2937.59	60.062 / 62.643	Aliphatic C–H stretching	Confirms organic components from sucrose and polyester resin.
1724.36	72.464 / 68.106	C=O stretching	Associated with ester carbonyl groups from polyester resin binder.
1579–1636	— / 73.887–73.952	Aromatic C=C / H–O–H bending	Related to resin structure and/or adsorbed water in the composite matrix.
1381.03	12.215 / 11.551	NO_3^- vibration / C–H bending	Supports the presence of nitrate ions from sodium nitrate.
1240–991	45.013–33.139 / 47.170–35.013	C–O/C–O–C stretching and ring vibration	Indicates oxygenated organic structures from sucrose and polyester resin.
470–866	47.987–80.641 / 54.034–83.147	Fingerprint region	Represents complex vibrations from nitrate, organic structures, and composite matrix interactions.

3.7. Combustion Behavior Interpretation

Integrating the burning-rate results with calorimetric data provides a coherent interpretation of the combustion behavior of the sodium nitrate–sucrose composite solid propellants. Activated carbon addition resulted in a statistically significant reduction in burning rate while increasing the measured calorific value. This combination indicates that activated carbon acts as a combustion-modifying additive that moderates flame propagation while improving the energetic output of the formulation, which may be associated with modifications in heat feedback and combustion pathways.

Overall, the combined assessment of physical integrity, statistically validated burning-rate measurements, calorific value data, FTIR characterization, and theoretical thermodynamic reference provides a laboratory-scale framework for evaluating formulation effects. The results indicate that activated carbon can serve as a regulating additive that influences the balance between combustion behavior and energy release in sodium nitrate–sucrose composite solid propellants.

It should be noted that this study is limited to material-level characterization under atmospheric conditions and does not include propulsion performance parameters such as thrust, chamber pressure, or specific impulse. Therefore, the findings should be interpreted as an initial evaluation of formulation effects rather than a complete propulsion system validation.

4. CONCLUSION

This study evaluated the effect of activated carbon addition on the combustion behavior and energetic characteristics of sodium nitrate–sucrose composite solid propellants. The addition of activated carbon resulted in a more controlled burning rate and showed a statistically significant difference based on Welch's t-test. Calorimetric results indicated an increase in calorific value from 3338 to 4111 cal g^{-1}, equivalent to 13.908–17.129 kJ g^{-1}, while the calculated reaction enthalpy (−968 cal g^{-1}) confirmed the exothermic nature of the base sodium nitrate–sucrose system. FTIR analysis indicated the presence of characteristic functional groups and suggested possible interactions among the composite components, supporting the role of activated carbon in modifying combustion behavior.

Activated carbon can act as a combustion-regulating additive that influences both burning behavior and energetic characteristics in sodium nitrate–sucrose composite formulations. However, this study is limited to laboratory-scale material evaluation under atmospheric conditions and does not include emission analysis, chamber pressure, thrust, or specific impulse measurements. Therefore, the findings should be interpreted as a preliminary assessment of formulation effects rather than complete propulsion or environmental performance validation.

5. AUTHOR'S DECLARATION

5.1. Supporting Information

The authors declare that no supporting information is available for this article.

5.2. Acknowledgements

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5.3. Conflict of Interest

The authors declare no conflict of interest regarding the publication of this manuscript.

5.4. Author Contributions

ARS conducted the experimental work, data analysis, and initial manuscript drafting. AM conceived the research idea, developed the study framework, interpreted the results, wrote and critically revised the manuscript, and served as the corresponding author. All authors discussed the results and approved the final version of the manuscript.

5.5. AI Statement

ChatGPT was utilized to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors. The final version of the manuscript was thoroughly reviewed to ensure accuracy, coherence, and alignment with the study's findings.

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