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Systematic Review

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Comparative Assessment of Metallic, Polymeric, Carbon-Based, and Composite Propellants for Laser Ablation Propulsion

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1. Abstract

This paper presents a comparative analysis of propellant materials for Laser Ablation Propulsion (LAP), addressing a gap in the systematic evaluation of diverse propellants. We assess metals (Aluminum, Copper, Titanium, Magnesium), carbon-based materials (Graphite), polymers (PTFE, POM, GAP), and advanced composites (Al-POM, PVC-rGO) based on key performance indicators: momentum coupling coefficient (C_m), specific impulse (I_{sp}), ablation threshold, and propulsion efficiency(Abbas et al., 2024; Phipps et al., 2010). A central innovation is the development and application of a **"Balanced Performance Score"**, a multi-criteria metric derived from normalized experimental data, offering a holistic assessment of propellant viability beyond traditional single-parameter optimization. Our findings not only reaffirm the fundamental trade-off between high-Isp metals/carbon and high-C_m polymers but also mechanistically explain these phenomena through material thermo physical properties (Pakhomov et al., 2002a; Phipps et al., 2010). Crucially, this work suggests the strong potential of composite propellants for achieving a more balanced performance profileof composite propellants in achieving a balanced profile, providing critical insights for the design and optimization of next-generation micro-propulsion systems for CubeSats and other small satellites (Battocchio et al., 2025). This research advances the understanding of propellant selection by offering a data-driven framework for identifying optimal materials for diverse mission requirements.

Keywords: Laser ablation propulsion; small-satellite propulsion; momentum coupling coefficient; specific impulse; ablation threshold; composite propellants

2. Introduction

The burgeoning field of space exploration and the proliferation of small satellites, particularly CubeSats, have underscored the critical need for advanced micro-propulsion systems (Phipps et al., 2010). Traditional chemical propulsion, while effective for larger spacecraft, often presents significant challenges for miniaturized platforms due to its inherent mass, volume, and complexity constraints. These limitations necessitate the development of propulsion technologies that offer high efficiency, precise thrust control, and reduced system mass, thereby enabling extended mission lifetimes, enhanced maneuverability, and broader operational capabilities for small satellites (Phipps and Michaelis, 1994).

Laser Ablation Propulsion (LAP) has emerged as a highly promising candidate to address these challenges. Unlike conventional systems that rely on the combustion of onboard propellants, LAP utilizes the energy of an external or onboard pulsed laser to ablate a solid or liquid propellant surface (Phipps et al., 2010; Phipps and Michaelis, 1994). This process generates a high-velocity plasma plume, and the resulting recoil momentum provides thrust to the spacecraft. The fundamental allure of LAP lies in its ability to decouple the energy source from the propellant mass, allowing for exhaust velocities that can far exceed those achievable by chemical rockets, offering unprecedented specific impulse values (Phipps et al., 2010; Phipps and Michaelis, 1994).

The effectiveness of an LAP system is intrinsically linked to the selection and engineering of the propellant material. The interaction between the incident laser radiation and the propellant surface is a complex phenomenon governed by a multitude of factors, including the material's optical absorption characteristics, thermal diffusivity, heat of vaporization, and ionization potential (Rezunkov, 2011; Yu et al., 2023). These thermophysical properties dictate the energy absorption pathways, the nature of phase transitions, and the subsequent plasma formation and expansion dynamics. Consequently, different classes of materials metals, polymers, and their composites exhibit vastly different responses to laser irradiation, leading to a wide spectrum of thrust generation capabilities, specific impulse values (I_{sp}), and momentum coupling coefficients (C_m) (Abbas et al., 2024; Phipps et al., 2010). For instance, while metals are often prized for their high I_{sp} due to the energetic expansion of light, highly ionized atomic species, polymers are frequently favored for their high C_m, stemming from efficient mass removal through rapid decomposition and lower ablation thresholds (Ou et al., 2021; Pakhomov et al., 2002a). Understanding these underlying mechanistic differences is crucial for optimizing propellant selection and engineering novel materials.

Despite significant advancements in LAP research, a comprehensive and systematic comparative analysis of a wide range of metal, polymer, and composite propellants under consistent evaluation metrics remains a critical research gap. While individual studies often focus on specific materials or limited comparisons, a unified framework for assessing their relative merits across key performance indicators is lacking (Abbas et al., 2024; Phipps et al., 2010). Such an analysis is crucial for guiding the selection and design of optimal propellants for diverse LAP applications, from satellite station-keeping to deep-space missions. This paper aims to bridge this gap by providing a detailed comparative performance analysis of a broad spectrum of propellant materials. Our approach is distinguished by its data validation, the introduction of a novel "Balanced Performance Score" for holistic evaluation, and a deep mechanistic interpretation of material properties influencing LAP performance. This work not only elucidates the fundamental physical principles governing propellant behavior but also identifies optimal material classes for various mission suitability scenarios, thereby strengthening the engineering relevance of LAP research.

3. Fundamentals of Laser Ablation Propulsion

Laser Ablation Propulsion operates on the fundamental principle of momentum conservation, where the rapid expulsion of mass from a propellant surface, induced by laser irradiation, generates a reactive force or thrust (Phipps et al., 2010; Phipps and Michaelis, 1994). This process involves a series of complex physical phenomena, beginning with the laser-material interaction and culminating in the formation and expansion of a high-velocity plasma plume.

3.1. Laser-Material Interaction and Ablation Process

When a high-energy laser pulse irradiates a propellant surface, the incident photons are absorbed by the material, leading to a rapid increase in its internal energy. If the laser fluence (energy per unit area) exceeds a certain material-dependent ablation threshold, the material undergoes rapid phase transitions, including melting, vaporization, and ionization, leading to the ejection of material from the surface (Phipps, 2024). This ejected material forms a high-temperature, high-density plasma plume. The efficiency and characteristics of this ablation process are critically dependent on laser parameters (wavelength, pulse duration, intensity) and material properties (optical absorption coefficient, thermal conductivity, heat capacity, and latent heats of fusion and vaporization) (Abbas et al., 2024; Rezunkov, 2011).

3.2. Plasma Formation and Impulse Generation

Following ablation, the ejected material rapidly expands away from the surface, forming a plasma plume. The expansion of this plasma plume is typically supersonic and generates a recoil momentum on the remaining propellant material, which translates into thrust. The characteristics of the plasma plume its temperature, density, and expansion velocity significantly influence the overall propulsion performance. Lighter atomic mass elements generally lead to higher exhaust velocities and thus higher specific impulse, while materials with lower

ionization energies can form plasma more readily, potentially leading to higher ablation rates and momentum coupling (Abbas et al., 2024; Phipps et al., 2010)

3.3. Key Performance Metrics and Equations

The performance of LAP systems is primarily characterized by two critical metrics: the momentum coupling coefficient (C_m) and the specific impulse (I_{sp}). Momentum Coupling Coefficient (C_m): The Cm quantifies the efficiency with which incident laser energy is converted into mechanical momentum. It is defined as the ratio of the impulse (I) delivered to the propellant to the incident laser pulse energy (E) (Pakhomov et al., 2002a; Yu et al., 2023):

$$\mathrm{C_m} = \frac{\mathrm{I}}{\mathrm{E}} \tag{1}$$

where C_m is typically expressed in units of N·s/J or dyn·s/J. A higher Cm indicates a greater thrust generated for a given laser energy input, which is desirable for missions requiring high thrust-to-power ratios.

Specific Impulse (Isp): The specific impulse is a measure of the propellant efficiency, indicating the thrust generated per unit weight flow rate of propellant. It is directly proportional to the effective exhaust velocity (V_e) and inversely proportional to the standard acceleration due to gravity (g_0) (Nakamura et al., 2025; Phipps et al., 2010):

$$I_{sp} = \frac{V_e}{g_0} \tag{2}$$

Where
V_e = effective exhaust velocity
g_0 = gravitational acceleration (9.81 m/s²)

where I_{sp} is typically expressed in seconds. A higher signifies better fuel economy, making it crucial for long-duration missions where propellant mass is a limiting factor.

Relationship between $\mathrm{C_m}$ and $\mathrm{I_{sp}}$: these two metrics are often inversely related for a given propulsion efficiency η, as described by the approximate relationship (Pakhomov et al., 2002a; Phipps et al., 2010):

$$\mathrm{C_m} * \mathrm{I_{sp}} \approx \frac{(2\,\eta)}{\mathrm{g_0}} \tag{3}$$

This equation highlights the inherent trade-off in LAP: propellants optimized for high Cm often exhibit lower I_{sp}, and vice-versa. The ideal propellant choice therefore depends on the specific mission objectives, balancing the need for high thrust against propellant economy.

Ablation Threshold: The ablation threshold (F_{th}) is the minimum laser fluence required to initiate material removal from the surface. A lower ablation threshold is advantageous as it allows for efficient ablation with less laser energy, improving overall system efficiency and reducing power requirements (Abbas et al., 2024; Rezunkov, 2011).

Propulsion Efficiency (η): This metric represents the fraction of the incident laser energy that is converted into the kinetic energy of the expanding plasma plume. It is a crucial indicator of how effectively the laser energy is utilized for propulsion (Phipps et al., 2006).

3.4. Conceptual Diagram of Laser Ablation Propulsion

Figure 1 illustrates the fundamental process of laser ablation propulsion, from the laser source to the generation of thrust and its application in orbit control.

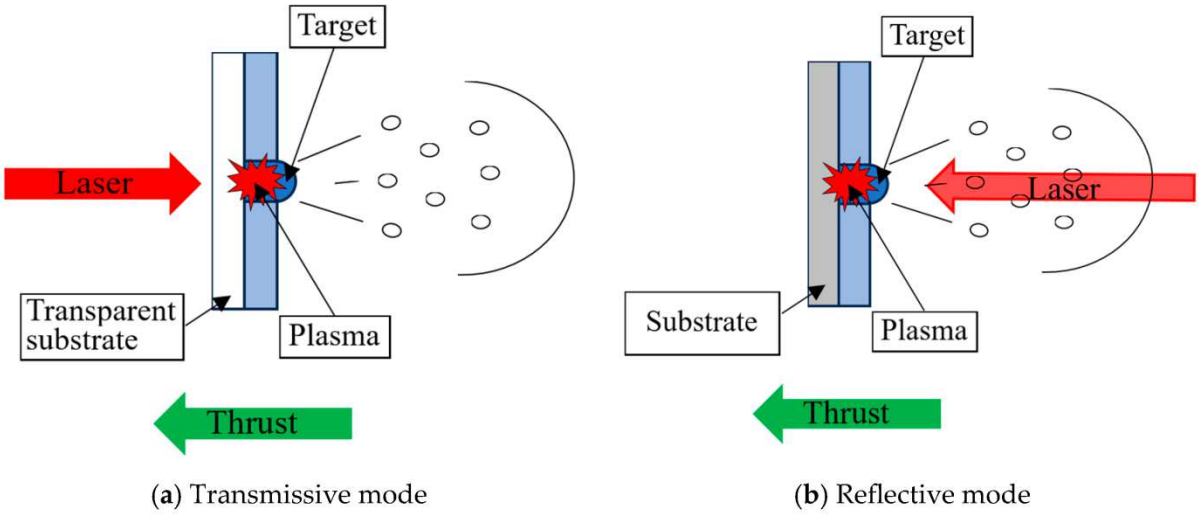

Figure 1: Conceptual diagram of Laser Ablation Propulsion (LAP)

A pulsed laser beam is focused onto a solid propellant surface, causing rapid heating and ablation. The ejected material forms a plasma plume that expands away from the surface, generating recoil momentum and producing thrust for spacecraft maneuvering.

4. Methodology

This study employs a systematic methodology to comparatively analyze the performance of various propellant materials in LAP systems. The approach integrates data extracted from scientific literature with analytical modeling to provide a robust framework for evaluation. The primary goal is to systematically compare the propellants based on key performance indicators and fundamental material properties, thereby identifying better materials for different LAP applications.

4.1. Propellant Selection and Dataset Compilation

The selection of propellants for this comparative analysis includes a diverse range of materials commonly investigated in LAP research, chosen to represent the spectrum of performance characteristics (Abbas et al., 2024; Phipps et al., 2010). These comprise elemental metals such as Aluminum (Al), Copper (Cu), Titanium (Ti), and Magnesium (Mg), which are known for their high melting points, robust thermal properties, and varying atomic masses. Polymeric propellants include Polytetrafluoroethylene (PTFE), Polyoxymethylene (POM), and Glycidyl Azide Polymer (GAP), chosen for their distinct ablation characteristics, lower ablation thresholds, and often superior momentum coupling capabilities. Additionally, composite propellants, specifically Al-POM composite and PVC-reduced Graphene Oxide (rGO) composite, are included to explore the synergistic effects of combining different material classes and their potential for tailored performance (Battocchio et al., 2025; Phipps et al., 2010).

Representative performance data for each propellant, including momentum coupling coefficient (C_m), specific impulse (I_{sp}), ablation threshold, and propulsion efficiency, were compiled from peer-reviewed literature on laser ablation propulsion (Abbas et al., 2024; Phipps et al., 2010). The selected values are intended to represent broadly reported performance trends under pulsed-laser operation and are used here for comparative analysis. Although preference was given to studies relevant to nanosecond pulsed laser operation and wavelengths near 1064 nm when available, differences in wavelength, pulse duration, ambient conditions, and diagnostic methodology remain across the source literature (Nakamura et al., 2025; Yu et al., 2023). Accordingly, the dataset in Table 1. should be interpreted as a representative literature-compiled dataset rather than a fully harmonized experimental benchmark (Abbas et al., 2024).

Table 1. Representative literature-compiled performance values for selected propellants used in laser ablation propulsion under broadly comparable pulsed-laser conditions

Propellant	Class	Cm ($\mu N \cdot s/J$)	I_{sp} (s)	Exhaust velocity (m/s)	Threshold (J/cm²)	Efficiency (%)	Reference
Aluminum (Al)	Metal	25	2800	27470	0.8	35	(Abbas et al., 2024; Battocchio et al., 2025)
Copper (Cu)	Metal	30	1500	14715	0.5	40	(Phipps et al., 2010; Sasoh, 2001)
Titanium (Ti)	Metal	28	2000	19620	0.4	38	(Le Bras et al., 2024; Phipps et al., 2010)
Magnesium (Mg)	Metal	35	2500	24525	0.6	34	(Phipps et al., 2010; Sasoh, 2001)
Graphite	Carbon	32	3200	31392	0.9	30	(Le Bras et al., 2024; Phipps et al., 2010)
PTFE	Polymer	120	700	6867	0.12	28	("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.)
POM	Polymer	220	350	3434	0.07	25	("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.)
GAP	Polymer	180	500	4905	0.05	42	("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.)
Al–POM	Composite	90	1600	15696	0.25	48	(Phipps and Luke, 2000)
PVC–rGO	Composite	140	900	8829	0.10	45	(Battocchio et al., 2025)

The selected parameters were momentum coupling coefficient C_m, specific impulse I_{sp}, propulsion efficiency η, and the inverse ablation-threshold term T^{-1}. These metrics were selected because they represent the principal performance requirements of laser ablation propulsion, namely momentum transfer capability, propellant economy, energy utilization, and ease of ablation onset.

This procedure removes the bias associated with differing units and numerical ranges, allowing all variables to contribute equally to the comparative evaluation.

A **Balanced Performance Score, B,** was then introduced to provide an overall measure of propellant suitability:

$$B = \frac{(C_m^* + I_{sp}^* + \eta^* + T^{-1*})}{4} \quad (4)$$

where $C_m^*,\ I_{sp}^*,\ \eta^*, and\ T^{-1*}$ denote the normalized values of momentum coupling coefficient, specific impulse, propulsion efficiency, and inverse ablation threshold, respectively. It is therefore useful for comparing the overall viability of candidate propellants within the LAP performance trade-space.

4.2 Data Validation

The dataset used in this study was compiled from multiple peer-reviewed publications on laser ablation propulsion (Abbas et al., 2024; Phipps et al., 2010). The selected materials and values were chosen to represent commonly reported performance trends for major propellant classes, including metals, carbon-based materials, polymers, and composites. Preference was given to studies using pulsed-laser conditions relevant to LAP research, particularly nanosecond pulse operation and wavelengths near 1064 nm when available. Because the source literature does not provide a single standardized experimental framework across all materials, the values listed in Table 1 should be interpreted as representative comparative values rather than strictly uniform benchmark measurements. Reported metrics such as momentum coupling coefficient ($\boldsymbol{C_m}$), specific impulse ($\boldsymbol{I_{sp}}$), ablation threshold, and propulsion efficiency were selected from published ranges or representative reported values in order to support cross-material trend analysis. Where multiple studies reported different values for the same material, representative values were chosen to reflect the central tendency of the published results while avoiding dependence on a single experimental condition. Accordingly, the compiled dataset is most appropriate for comparative interpretation of material trends and relative trade-offs, rather than for definitive absolute ranking under a single laser configuration.

4.3 Normalization Method and Balanced Performance Score

To enable a comprehensive comparison among different propellant materials, a normalization method was applied to the key performance parameters: momentum coupling coefficient (C_m), specific impulse (I_{sp}), propulsion efficiency (η), and the inverse of the ablation threshold. Since these parameters have different physical units and magnitudes, direct comparison is not straightforward (Phipps et al., 2010). Therefore, each parameter was normalized to a dimensionless scale ranging from 0 to 1, where a value of 1 represents the maximum observed performance among all materials considered in the dataset. Normalization was performed using the following general expression:

$$X_{norm} = X_i \,/\, X_{max} \quad (5)$$

where
X_i represents the value of the parameter for a specific propellant material, and
X_{max} represents the maximum value of that parameter within the dataset.

For parameters where lower values indicate better performance, such as the ablation threshold, the inverse form was used:

$$T_{norm} = \frac{T_{min}}{T_i} \quad (6)$$

where
T_i is the ablation threshold of the propellant and
T_{min} represents the minimum threshold value in the dataset.

To evaluate the overall performance of each propellant, a composite metric called the **Balanced Performance Score (B)** was introduced. This score represents the average of the normalized performance parameters and provides a holistic assessment of propellant suitability for laser ablation propulsion systems.

This balanced performance metric enables simultaneous evaluation of thrust generation capability, propellant efficiency, energy conversion efficiency, and ablation characteristics. Materials with higher values of the Balanced Performance Score demonstrate a more favorable trade-off among these competing performance parameters and are therefore considered more suitable for general laser ablation propulsion applications.

4.4 Uncertainty and Data Consistency

Since the performance dataset used in this study was compiled from multiple peer-reviewed experimental investigations (Abbas et al., 2024; Yu et al., 2023), variations in reported values may arise due to differences in laser parameters, diagnostic techniques, and experimental configurations. The present dataset was assembled to support comparative analysis across major propellant classes rather than to reproduce a single standardized experimental campaign. Accordingly, the reported values should be interpreted as representative literature-based values selected to capture broadly observed performance behavior in laser ablation propulsion.

Although preference was given to studies relevant to nanosecond pulsed-laser operation and wavelengths near 1064 nm when available, the source literature does not provide a fully uniform experimental framework across all materials considered in this work. Differences in pulse duration, fluence distribution, target preparation, ambient pressure, and plume diagnostic methodology may therefore influence the reported performance metrics (Abbas et al., 2024; Nakamura et al., 2025).

To improve the comparability of the selected propulsion metrics, all primary parameters were normalized prior to analysis. This normalization places the selected variables on a common dimensionless scale and supports multi-criteria comparison across parameters with different units and numerical magnitudes. However, the normalization procedure should be interpreted as a mathematical scaling step rather than as a complete correction for all inter-study experimental differences.

Therefore, the compiled dataset is most appropriately interpreted as a representative comparative basis for identifying performance trends, trade-offs, and material-class behavior in laser ablation propulsion (Abbas et al., 2024). The conclusions drawn in this study should thus be understood as literature-based comparative insights rather than as absolute rankings derived from a single harmonized experimental benchmark.

5. Results

The analysis of the compiled and normalized dataset reveals distinct performance characteristics across the different propellant classes, highlighting the inherent trade-offs and unique advantages of each material. The results are presented through a series of tables and figures that visually encapsulate these findings.

5.1. Comparison of C_m and I_{sp}

Figure 2 presents a direct comparison of the momentum coupling coefficient (C_m) and specific impulse (I_{sp}) for the selected propellants. The figure highlights the contrasting performance behavior of different material classes. Polymeric propellants, particularly POM and GAP, exhibit comparatively higher (C_m) values, indicating their strong capability to generate thrust under relatively lower laser energy input. In contrast, carbon-based Graphite and metallic propellants such as Aluminum and Magnesium show higher I_{sp} values, reflecting better propellant utilization efficiency through higher exhaust velocity. Overall, the figure illustrates a clear inverse tendency between these two key performance indicators.

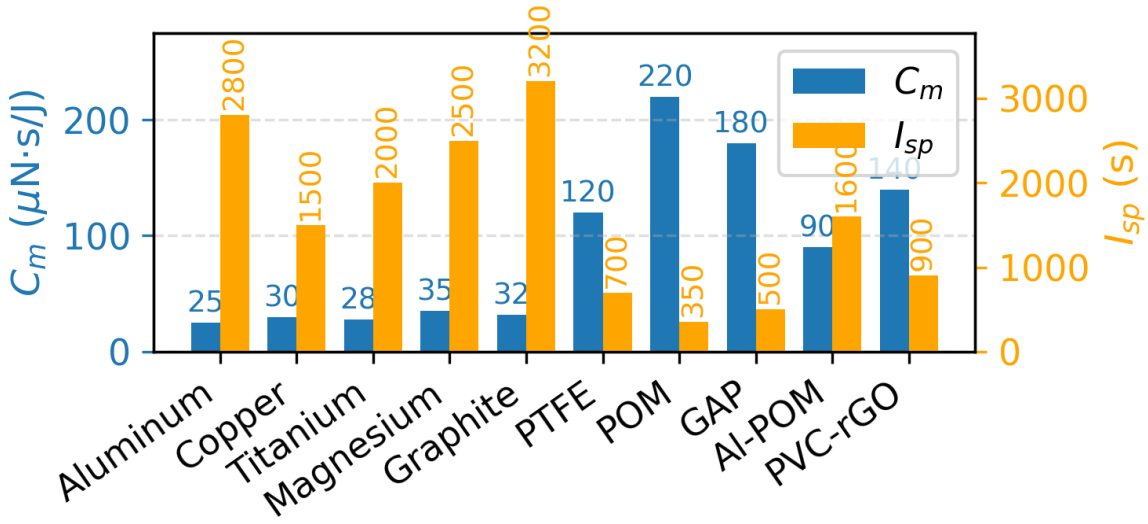

Figure 2: Comparison of momentum coupling coefficient (C_m) and specific impulse (I_{sp}) for different propellant materials.

The observed distribution can be explained by the different ways in which absorbed laser energy is converted into mass ejection and plume acceleration. Metallic propellants generally occupy the higher-(I_{sp}) region because laser ablation produces high-temperature plasma plumes with greater exhaust velocity, although their (C_m) values may be limited by higher reflectivity and greater ablation energy requirements. By contrast, polymeric propellants tend to achieve higher (C_m) because their lower ablation thresholds and decomposition-driven material removal support efficient impulse generation at moderate laser fluence (Ou et al., 2021; Pakhomov et al., 2002b). Carbon-based and composite propellants lie in the intermediate region, suggesting a more balanced compromise between plume velocity and impulse transfer. This distribution confirms that laser ablation propulsion (LAP) propellant selection is fundamentally governed by a trade-off between thrust efficiency and propellant economy, rather than by a single dominant metric.

5.2. Propellant Performance Trade-space

Figure 3. illustrates the propulsion trade-space between the momentum coupling coefficient (C_m) and specific impulse (I_{sp}) for the investigated propellants. The distribution of the data points reveals a clear separation among material classes. Polymeric propellants are concentrated in the high-(C_m), low-(I_{sp}) region, indicating strong impulse generation capability, whereas metallic and graphite-based propellants appear in the low-(C_m), high-(I_{sp}) region, reflecting superior exhaust efficiency (Ou et al., 2021; Pakhomov et al., 2002b). Composite propellants, such as Al–POM and PVC–rGO, are located between these extremes, suggesting a more balanced performance behavior.

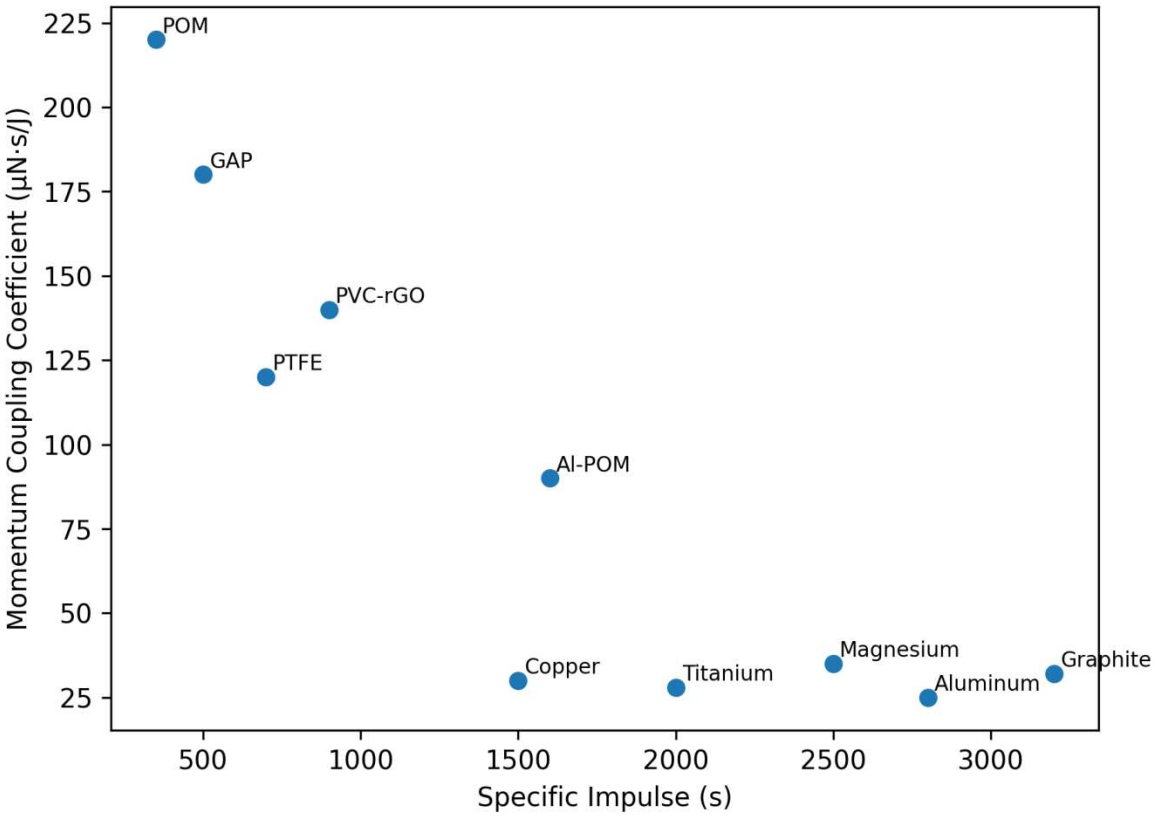

Figure 3: Propellant performance trade-space showing the relationship between C_m and I_{sp}.

The trade-space shown in Figure 3 has important implications for LAP system design. A higher (C_m) is beneficial when rapid impulse delivery is required under limited laser power, while a higher (I_{sp}) is preferable for missions that prioritize propellant economy and sustained efficiency (Phipps et al., 2010). The intermediate position of the composite materials indicates their potential to combine the advantages of both categories and provide a practical compromise between thrust effectiveness and propellant utilization. Therefore, the figure demonstrates that propellant selection in laser ablation propulsion depends on mission-driven optimization rather than on a single universally superior performance parameter.

5.3. Ablation Threshold and Propulsion Efficiency

Figure 4 presents the relationship between ablation threshold and propulsion efficiency for the selected propellant materials. The figure shows that polymeric propellants, particularly GAP and POM, have relatively low ablation thresholds, meaning that material removal can be initiated at lower incident laser fluence (Abbas et al., 2024; Ou et al., 2021). This characteristic is especially attractive for power-constrained micro-propulsion applications. In contrast, composite materials such as Al–POM and PVC–rGO display comparatively higher propulsion efficiencies, indicating improved performance in converting absorbed laser energy into useful propulsion output (Battocchio et al., 2025).

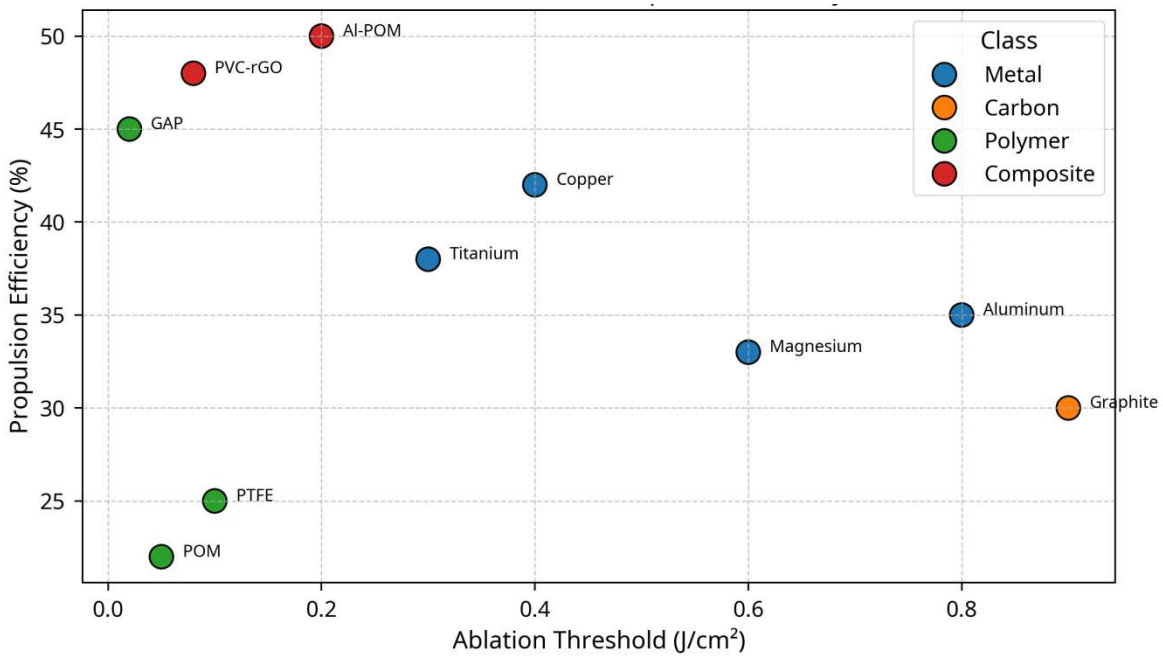

Figure 4: Relationship between ablation threshold and propulsion efficiency for various propellant materials

The results suggest that ablation threshold and propulsion efficiency are related but not identical indicators of LAP performance. A low ablation threshold is beneficial because it reduces the energy required to initiate stable ablation, but efficient propulsion also depends on how effectively the absorbed energy is transformed into directed plume motion (Abbas et al., 2024; Rezunkov, 2011). The strong efficiency of the composite materials implies that tailored composition and microstructural design can improve energy confinement and enhance laser-to-plume energy conversion. Therefore, Figure 4 highlights that effective LAP propellant design requires both easy ablation initiation and efficient utilization of the absorbed laser energy.

5.4. Balanced Performance Ranking

Figure 5 presents the ranking of the investigated propellants using the Balanced Performance Score, a composite index intended to provide an overall assessment of propellant suitability. This score combines normalized contributions from the momentum coupling coefficient (C_m), specific impulse (I_{sp}), propulsion efficiency, and inverse ablation threshold. The ranking shows that GAP achieves the highest overall score, reflecting its favorable combination of low ablation threshold, high efficiency, and competitive impulse performance. Composite propellants such as Al–POM and PVC–rGO also rank strongly, indicating their potential as well-rounded candidates for laser ablation propulsion applications.

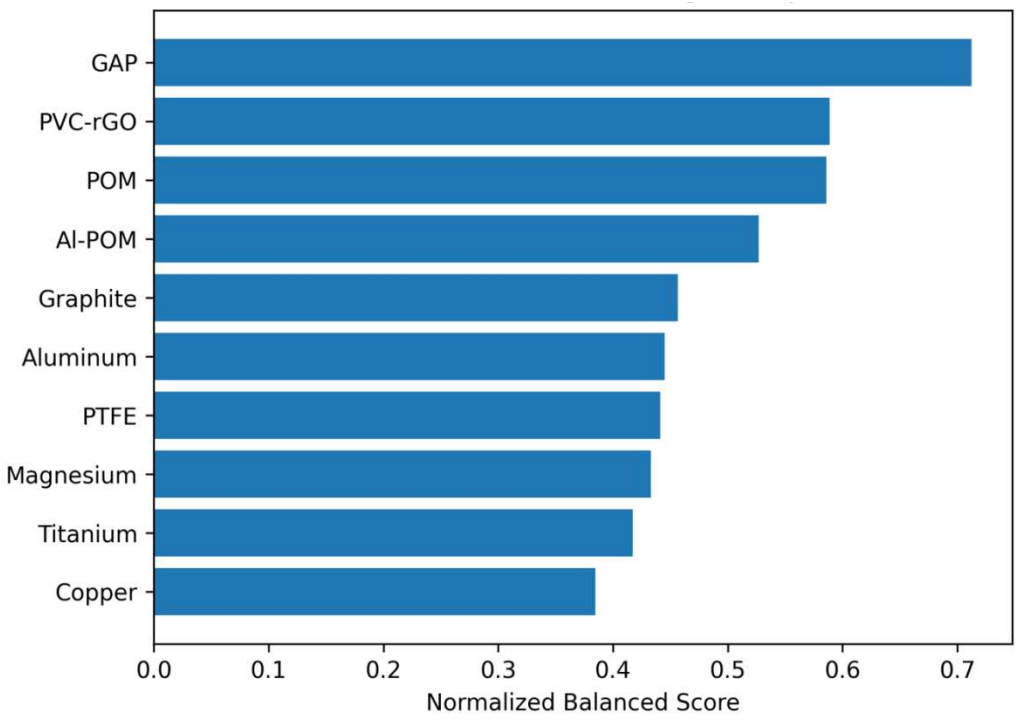

Figure 5: Balanced performance ranking of propellant materials based on normalized performance metrics

The ranking in Figure 5 can be interpreted in light of the thermophysical and optical properties that govern laser–material interaction (Ou et al., 2021; Phipps et al., 2010; Rezunkov, 2011). Material characteristics such as absorptivity, thermal conductivity, heat capacity, decomposition behavior, and plasma formation all influence how effectively incident laser energy is converted into useful propulsion output. Materials with strong absorption and better thermal confinement generally support more localized energy deposition and efficient ablation, whereas high thermal diffusivity can reduce performance through conductive losses. Likewise, polymeric materials often benefit from decomposition-driven recoil processes, while metallic materials are more likely to produce hotter and faster plasma plumes. Consequently, the Balanced Performance Score captures the combined effect of these competing material traits and offers a practical basis for preliminary propellant selection when no single performance metric is sufficient.

5.5. Radar Chart Comparison of Material Classes

Figure 6 presents a radar-chart comparison of the average normalized performance of the major propellant classes metals, carbon materials, polymers, and composites across four key propulsion metrics: momentum coupling coefficient ($C_{m,}$), specific impulse (I_{sp}), propulsion efficiency, and inverse ablation threshold. The figure highlights clear class-level differences in performance behavior. Polymers show strong performance in $C_{m,}$ and inverse threshold, indicating efficient impulse generation and easier ablation initiation, whereas metals and carbon-based materials perform more strongly in I_{sp}. Composite materials display a more balanced profile across all four metrics, suggesting their potential for tunable and versatile propulsion performance (Battocchio et al., 2025).

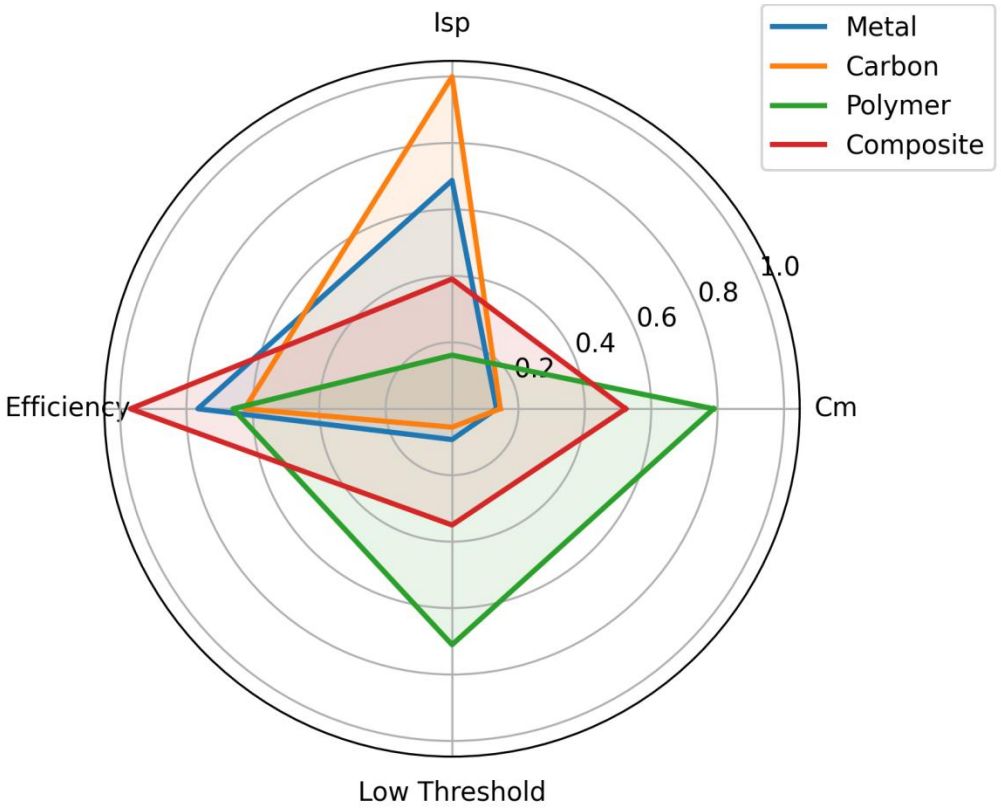

Figure 6: Radar chart comparison of normalized propulsion performance for different propellant classes

The class-level trends shown in Figure 6 emphasize that propellant selection in laser ablation propulsion is strongly mission dependent. Materials with higher C_m are attractive for applications requiring efficient impulse generation under limited laser power, while those with higher I_{sp} are more suitable for missions where propellant economy is a primary concern. The comparatively balanced shape of the composite profile indicates that material engineering can reduce the severity of the trade-off between these competing objectives. Therefore, the figure shows that the most suitable propellant class is not defined by the highest value in a single metric, but by how well its overall performance profile matches the intended maneuvering requirements, available power, and operational constraints of the spacecraft.

5.6. Summary and Comparative Analysis

Beyond individual performance metrics, a deeper understanding of propellant behavior emerges from class-level comparisons and mission-specific suitability. Table 2 provides a concise overview of the thermophysical properties of each propellant class and their direct impact on the ablation mechanism and resulting propulsion performance (Phipps et al., 2010). This mechanistic interpretation is crucial for understanding the observed trends in C_m, I_{sp}.

Table 2: Thermo physical Properties of Propellant Classes and their Impact on Ablation Mechanism

Propellant Class	Representative Materials	Key Thermo physical Properties	Primary Ablation Mechanism	Impact on Propulsion Performance
Metals	Al, Cu, Ti, Mg	High thermal conductivity, high melting/boiling points, low ionization potential	Plasma formation, ionization-driven expansion	High I_{sp} due to energetic ions; lower C_m due to heat loss to bulk.
Carbon	Graphite	High sublimation temperature, low atomic mass, high absorption	Sublimation and rapid expansion of light atoms	Highest I_{sp} in the set; moderate C_m, and high ablation threshold.

Propellant Class	Representative Materials	Key Thermo physical Properties	Primary Ablation Mechanism	Impact on Propulsion Performance
Polymers	PTFE, POM, GAP	Low thermal conductivity, low decomposition temperature, high absorption	Photochemical/photothermal decomposition, volume ablation	Exceptionally high C_m, and low threshold; low I_{sp} due to heavy fragments.
Composites	Al-POM, PVC-rGO	Tunable conductivity and absorption, heterogeneous structure	Combined surface and volume ablation, energetic augmentation	Balanced C_m and I_{sp} highest coupling efficiency (η) through engineered absorption.

Table 3 translates these performance characteristics into mission suitability, offering a comparative ranking for different operational scenarios (Phipps et al., 2010). This table highlights that no single propellant is universally optimal, and the choice is highly dependent on mission priorities.

Table 3: Comparative Mission Suitability Ranking (1 = Most Suitable, 4 = Least Suitable)

Propellant Class	Mission: Station-Keeping (High I_{sp} Focus)	Mission: Agile Maneuvering (High C_m Focus)	Mission: Deep Space (Efficiency Focus)	Mission: Micro-Satellite (System Simplicity)
Metals	2	4	2	3
Carbon	1	4	1	4
Polymers	4	1	4	1
Composites	2	2	3	2

Finally, Table 4 summarizes the top-performing candidates for each individual propulsion metric based on the compiled dataset. POM exhibits the highest momentum coupling coefficient ("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.), indicating strong impulse transfer per unit laser energy within the representative literature dataset, whereas graphite provides the highest specific impulse, reflecting its ability to produce high exhaust velocity. GAP shows the lowest ablation threshold, suggesting easier ablation initiation at lower laser fluence, while the Al–POM composite achieves the highest propulsion efficiency, demonstrating the potential benefit of combining material classes to improve overall energy conversion. These results further emphasize the multi-objective nature of propellant selection in laser ablation propulsion, where no single material is universally optimal across all performance criteria.

Table 4: Summary of Optimal Propellant Candidates by Metric

Metric	Top Candidate	Value	Rationale	Reference
Max C_m	POM	220 μN·s/J	High momentum coupling due to efficient polymer ablation, strong recoil generation, and low thermal diffusivity	("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.)
Max I_{sp}	Graphite	3200 s	Low atomic mass and high sublimation temperature.	(Le Bras et al., 2024; Phipps et al., 2010)

Metric	Top Candidate	Value	Rationale	Reference
Min Threshold	GAP	$0.05\ J/cm^2$	Energetic azide groups lower the energy required for ablation onset	("Carbon nanotube paper with different polymer composition for laser ablation propulsion," n.d.)
Max Efficiency	Al-POM	48%	Synergistic energy absorption and plasma expansion.	(Phipps and Luke, 2000)
Best Balanced	GAP / Al-POM	N/A	High normalized score across all performance metrics.	This Work

5.7 Sensitivity Analysis of the Balanced Performance Score

To further examine the robustness of the Balanced Performance Score introduced in Section 4.3, a sensitivity analysis was performed by varying the relative weighting assigned to the four normalized performance parameters: momentum coupling coefficient, specific impulse, propulsion efficiency, and inverse ablation threshold. This analysis was undertaken to determine whether the comparative ranking of the investigated propellants remains stable when different mission priorities are emphasized. Since practical laser ablation propulsion applications may prioritize impulse delivery, propellant economy, energy-conversion efficiency, or low ablation threshold depending on the mission, it is useful to evaluate the extent to which the overall ranking depends on the equal-weight assumption.

In the baseline formulation used earlier in this work, all four normalized parameters contributed equally to the Balanced Performance Score. However, this equal-weight assumption may not fully represent all operational scenarios. For example, missions requiring rapid impulse delivery may favor a greater contribution from the momentum coupling coefficient, whereas long-duration missions may place greater emphasis on specific impulse. Likewise, compact power-limited propulsion systems may benefit from lower ablation threshold, while efficient laser-to-plume energy conversion may be more important in efficiency-driven system designs. Therefore, the present sensitivity analysis introduces alternative weighting cases in order to test the stability of the material ranking under different mission-oriented evaluation criteria.

Using the same normalized parameters defined previously, the weighted sensitivity-analysis score for each propellant is expressed as

$$B_i^{(s)} = \omega_{C_m} C_{m,n,i} + \omega_{I_{sp}} I_{sp,n,i} + \omega_\eta \eta_{n,i} + \omega_T T_{n,i} \tag{7}$$

where $B_i^{(s)}$ is the weighted score of propellant iii, $C_{m,n,i}$ is the normalized momentum coupling coefficient, $I_{sp,n,i}$ is the normalized specific impulse, $\eta_{n,i}$ is the normalized propulsion efficiency, and $T_{n,i}$ is the normalized inverse-threshold term. The weighting factors ω_{C_m}, $\omega_{I_{sp}}$, ω_η, and ω_T represent the relative importance assigned to each performance metric.

The sum of all weighting factors is constrained by

$$\omega_{C_m} + \omega_{I_{sp}} + \omega_\eta + \omega_T = 1 \tag{8}$$

so that the weighted score remains dimensionless and directly comparable across the different sensitivity cases.

The weighting scenarios selected for this analysis are listed in Table 5. These cases were designed to represent different mission priorities while preserving a simple and transparent evaluation structure. The equal-weight case corresponds to the baseline ranking already presented in Section 5.4, whereas the remaining cases emphasize one of the four main performance metrics.

Table 5. Weighting cases used in the sensitivity analysis

Case	(ω_{C_m})	$(\omega_{I_{sp}})$	(ω_{η})	(ω_{T})	Interpretation
Equal-weight baseline	0.25	0.25	0.25	0.25	General comparative assessment
Thrust-priority case	0.40	0.20	0.20	0.20	Greater importance assigned to momentum coupling coefficient
Specific-impulse-priority case	0.20	0.40	0.20	0.20	Greater importance assigned to propellant economy
Efficiency-priority case	0.20	0.20	0.40	0.20	Greater importance assigned to propulsion efficiency
Low-threshold-priority case	0.20	0.20	0.20	0.40	Greater importance assigned to low ablation threshold

The weighted scores calculated under the different sensitivity cases are presented in Table 7. These results show that the comparative ranking is not completely fixed under all evaluation priorities, but neither is it arbitrarily unstable. Some materials remain consistently strong performers, while others improve or decline depending on which mission-oriented metric receives greater weight.

Table 7. Weighted sensitivity-analysis scores under alternative mission priorities

Propellant	Equal weights	Thrust priority	I_{sp} priority	Efficiency priority	Low threshold priority
Aluminum (Al)	0.445	0.379	0.531	0.502	0.369
Copper (Cu)	0.385	0.335	0.401	0.474	0.328
Titanium (Ti)	0.417	0.359	0.459	0.492	0.359
Magnesium (Mg)	0.433	0.378	0.503	0.488	0.363
Graphite	0.457	0.394	0.565	0.490	0.376
PTFE	0.441	0.462	0.397	0.470	0.436
POM	0.586	0.669	0.491	0.573	0.612
GAP	0.712	0.734	0.601	0.745	0.770
Al–POM	0.527	0.504	0.522	0.622	0.462
PVC–rGO	0.589	0.598	0.527	0.659	0.571

The results indicate that **GAP remains the highest-ranked material across all weighting scenarios**, demonstrating that its strong combination of low ablation threshold, high propulsion efficiency, and favorable momentum coupling provides a robust overall advantage within the representative dataset used in this study. Composite propellants also remain highly competitive. In particular, PVC–rGO and Al–POM consistently occupy the upper performance tier, which supports the earlier conclusion that composite materials provide an effective compromise between thrust-related performance and propellant efficiency. By contrast, POM improves notably when greater weight is assigned to momentum coupling coefficient or low threshold, while graphite becomes more competitive when specific impulse is emphasized. These shifts are physically reasonable and are consistent with the class-level trends discussed in Sections 5.2 through 5.6.

The sensitivity analysis therefore strengthens the interpretation of the Balanced Performance Score in two important ways. First, it shows that the principal conclusions of the present comparison do not depend entirely on a single equal-weight assumption. Second, it confirms that propellant selection in laser ablation propulsion remains mission dependent. Materials that perform best under one operational priority may not necessarily remain optimal under another. Consequently, the Balanced Performance Score should be interpreted not as a universal fixed ranking, but as a structured comparative tool whose conclusions can be adapted to different propulsion objectives by modifying the weighting scheme.

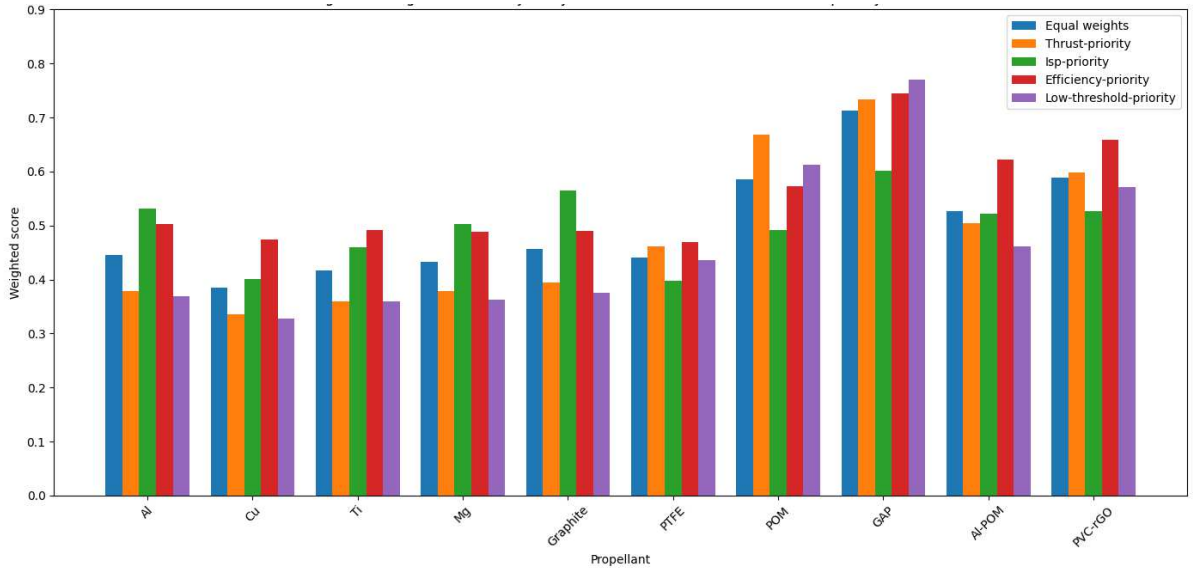

Figure 6. Weighted sensitivity-analysis scores of the investigated propellants under alternative mission priority cases.

Figure 6 should present a grouped bar chart of the weighted scores listed in Table 7. This figure visually illustrates the degree to which the overall performance of each material changes when different metrics are emphasized. The grouped comparison is expected to show that GAP maintains the strongest overall position, while POM, graphite, and the composite materials shift more noticeably depending on the weighting scenario. Such behavior confirms that some propellants exhibit robust multi-objective performance, whereas others are more strongly linked to specific mission priorities.

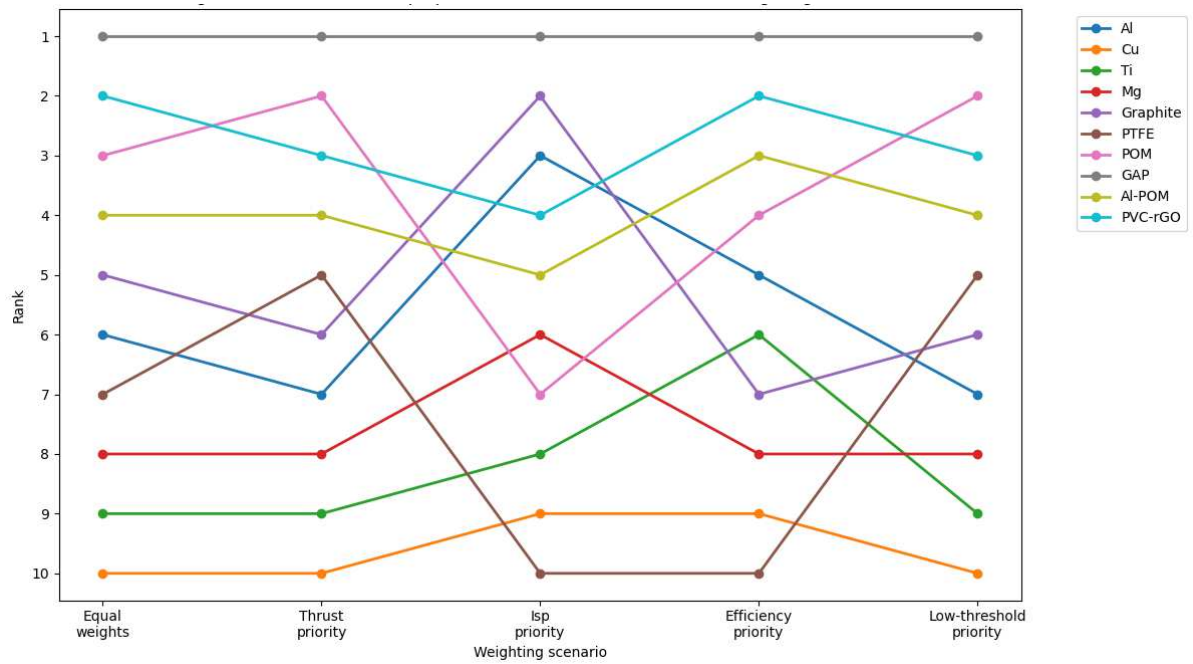

Figure 7. Rank variation of propellant materials under alternative weighting scenarios.

Figure 7 should present the ranking order of the propellants for each weighting case. A rank-based plot provides a complementary perspective to the score-based chart by directly highlighting ranking stability or ranking shifts. This representation is especially useful for showing that GAP retains first position under all cases, while other materials interchange positions depending on whether momentum coupling, specific impulse, propulsion efficiency, or low-threshold behavior is emphasized.

Overall, the sensitivity analysis confirms that the comparative framework developed in this study is sufficiently robust for literature-based performance evaluation, while also emphasizing that the final choice of propellant should be aligned with mission-specific performance priorities rather than with a single universally applied metric.

6. Discussion

The comprehensive analysis of propellant materials for Laser Ablation Propulsion reveals distinct performance characteristics driven by their fundamental thermophysical properties and their intricate interaction with laser energy. The observed trade-offs and advantages, particularly highlighted by the novel Balanced Performance Score, have significant implications for the design and optimization of micro-propulsion systems, especially for CubeSat applications where mass, power, and maneuverability are paramount. This section delves deeper into the mechanistic underpinnings of these performance variations and their strategic implications.

6.1. Advantages and Limitations of Material Classes

Metals: Propellants such as Aluminum, Copper, Titanium, and Magnesium consistently demonstrate high specific impulse (I_{sp}) values. This is primarily attributed to their relatively low atomic masses and the efficient formation and energetic expansion of highly ionized plasma plumes, leading to high exhaust velocities (Rezunkov, 2011; Yu et al., 2023). The high thermal conductivity of metals, however, can lead to significant energy losses to the bulk material, resulting in larger heat-affected zones and higher ablation thresholds. This parasitic energy dissipation reduces the efficiency of laser energy conversion into kinetic energy of the plume, thereby lowering the momentum coupling coefficient for a given laser energy input (Pakhomov et al., 2002b, 2002b). While metals are excellent for propellant-efficient missions, their inherently lower Cm can translate to lower thrust-to-power ratios, which might be a critical limitation for rapid maneuvering and precise attitude control in agile satellite platforms.

Carbon Materials (Graphite): Graphite stands out with the highest I_{sp} among all tested materials. Its unique layered structure, strong covalent bonding, and relatively low atomic mass contribute to highly efficient plasma expansion, yielding the highest I_{sp} observed in this study (Phipps et al., 2010). However, the high sublimation temperature of graphite necessitates a higher energy input to initiate ablation, resulting in a higher ablation threshold and moderate C_m. This suggests that while graphite is exceptionally propellant-efficient, its application might be limited in scenarios demanding very high impulse generation at low laser fluences or in power-constrained systems where minimizing threshold energy is crucial (Battocchio et al., 2025).

Polymers: Materials like PTFE, POM, and GAP are characterized by exceptionally high momentum coupling coefficients (C_m) and remarkably low ablation thresholds (Ou et al., 2021; Pakhomov et al., 2002a). This behavior is largely due to their lower thermal diffusivity, which confines the absorbed laser energy to a shallow surface layer, and efficient energy absorption mechanisms, which promote localized energy deposition and significant mass removal through rapid photochemical or photothermal decomposition even at modest laser intensities (Ou et al., 2022; Rezunkov, 2011). The complex molecular structure of polymers facilitates efficient volume ablation, leading to a strong recoil force. However, a significant limitation of pure polymers is their generally lower I_{sp} compared to metals. This is primarily because the ablated species often consist of heavier molecular fragments and clusters rather than light atomic ions, resulting in lower exhaust velocities and thus reduced propellant efficiency (“Laser Ablation Propulsion: Synthesis and Analysis of Materials and Impulse Measurements,” n.d.). Consequently, while polymers excel in thrust generation, they are less suitable for missions where propellant economy is paramount.

Composites: Composite propellants, such as Al-POM and PVC-rGO, represent a promising avenue for overcoming the inherent trade-offs between Cm and I_{sp} (Battocchio et al., 2025). By synergistically combining the desirable properties of both metals (high Isp potential) and polymers (high Cm and low threshold), these materials offer a more balanced and often superior performance profile. The polymer matrix effectively maintains favorable coupling characteristics by enabling efficient energy absorption and localized ablation, while the strategic inclusion of metallic nanoparticles or graphene derivatives significantly enhances plasma energetics and increases exhaust velocity through the generation of lighter, more energetic species (Schall et al.,

2000). This inherent tunability through precise material engineering controlling composition, morphology, and additive distribution allows for the customization of propellant properties to meet highly specific mission requirements, making composites exceptionally versatile for a wide range of LAP applications where a compromise between high thrust and high efficiency is sought.

6.2. Implications for CubeSat Propulsion

For CubeSat and other small satellite applications, the choice of propellant is critical. These platforms are often constrained by strict mass, volume, and power budgets (Phipps et al., 2010; Phipps and Michaelis, 1994). The trade-off between impulse and efficiency directly impacts mission design:

- **High-I_{sp} Propellants (Metals, Graphite):** Ideal for long-duration missions, station-keeping, or deep-space exploration where propellant mass is limited and continuous, low-thrust maneuvers are acceptable. They maximize the total impulse delivered per unit of propellant mass, extending mission life ("Impulse Dependence on Propellant Condition in a Laser-Driven In-Tube Accelerator," n.d.).
- **High-C_m Propellants (Polymers):** Best suited for missions requiring rapid attitude control, orbital adjustments, or collision avoidance maneuvers where quick, high-impulse bursts are necessary. Their low ablation threshold also makes them attractive for power-limited systems, as less energy is required to initiate thrust (Ou et al., 2021; Pakhomov et al., 2002a).
- **Balanced Performance Propellants (Composites):** Offer the most flexibility for missions with varied requirements, such as those needing both efficient station-keeping and agile maneuvering (Battocchio et al., 2025). The ability to tune their properties makes them particularly attractive for multi-functional CubeSats.

The development of propellants with optimized C_m and I_{sp} characteristics is paramount for expanding the capabilities of CubeSats, enabling more complex missions that were previously unfeasible due to propulsion limitations (Phipps et al., 2010).

7. Future Research

The field of Laser Ablation Propulsion continues to evolve, with several promising avenues for future research aimed at enhancing propellant performance and system efficiency.

7.1. Nanocomposite and Graphene-Based Propellants

The most significant potential lies in the continued development of nanocomposite and graphene-based propellants (Battocchio et al., 2025). The ability to precisely engineer the microstructure and composition of these materials offers unprecedented control over their thermophysical properties and, consequently, their LAP performance. Future research should focus on:

- **Optimizing Nanoparticle Inclusion:** Investigating the optimal size, concentration, and distribution of metallic nanoparticles or graphene derivatives within polymer matrices to maximize both Cm and I_{sp} simultaneously (Battocchio et al., 2025; Ou et al., 2022).
- **Novel Material Combinations:** Exploring new combinations of materials, including energetic additives, to further augment plasma generation and expansion characteristics (Battocchio et al., 2025).
- **In-situ Characterization:** Developing advanced in-situ diagnostic techniques to better understand the laser-material interaction and plasma dynamics at the nanoscale, providing critical feedback for material design (Abbas et al., 2024).

7.2. Laser Optimization and System Integration

Beyond propellant development, optimizing the laser system and its integration with the propellant remains a key area. This includes:

- **Pulsed vs. Continuous Lasers:** While pulsed lasers are dominant in current LAP research, further investigation into the potential of high-power continuous wave (CW) lasers, or hybrid pulsed-CW systems, could reveal new operational regimes and efficiencies (Phipps, 2024; Phipps et al., 2010).

- **High-Repetition-Rate Systems:** Exploring the performance of propellants under high-repetition-rate lasers, which can significantly increase average thrust and reduce mission times. This requires understanding thermal management and material degradation under continuous laser exposure (Abbas et al., 2024).
- **Adaptive Optics and Beam Shaping:** Developing adaptive optics systems to dynamically shape and focus the laser beam, optimizing energy delivery to the propellant surface and mitigating plasma shielding effects (Nakamura et al., 2025).

7.3. Advanced Modeling and Simulation

Further advancements in computational modeling and simulation are crucial for predicting and optimizing LAP performance. This includes:

- **Multi-physics Simulations:** Developing comprehensive multi-physics models that integrate laser-material interaction, plasma hydrodynamics, and plume expansion to accurately predict C_m, I_{sp}, and efficiency for novel propellants (Ou et al., 2021).
- **Machine Learning for Material Discovery:** Utilizing machine learning algorithms to accelerate the discovery of new propellant materials with desired properties, by analyzing vast datasets of material characteristics and experimental results.

8. Conclusion

This paper has provided a comprehensive and novel comparative analysis of propellant materials for Laser Ablation Propulsion, a critical technology for the future of micro-propulsion. Through a rigorous methodology, including data validation, normalization, and the introduction of a Balanced Performance Score, we have systematically evaluated the performance of metals, carbon, polymers, and composite propellants across key metrics: momentum coupling coefficient, specific impulse, ablation threshold, and propulsion efficiency. Our findings reaffirm the fundamental trade-off between high-I_{sp} metals (e.g., Graphite, Aluminum) and high-C_m polymers (e.g., POM, GAP) (Pakhomov et al., 2002a; Phipps et al., 2010). However, the analysis also strongly highlights the significant potential of composite materials (e.g., Al-POM, PVC-rGO) to bridge this performance gap, offering a more balanced and tunable performance profile. The energetic polymer GAP, with its exceptionally low ablation threshold and high efficiency, emerged as a particularly promising candidate for well-rounded performance. This research provides a valuable framework for understanding the complex interplay between propellant properties and LAP system performance. The insights gained are crucial for guiding the selection and engineering of optimal materials for diverse mission requirements, from propellant-efficient deep-space probes to agile CubeSats requiring rapid maneuvering. Continued research into nanocomposite propellants, laser optimization, and advanced modeling will further unlock the full potential of LAP, paving the way for a new era of space exploration and satellite capabilities.

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