Journal of Informatics Education and Research
ISSN: 1526-4726
Vol 6 Issue 1 (2026)

Integration of Green Propellants in Advanced Chemical Propulsion Systems: Challenges and Innovations for Future Rocketry

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Abstact:

This paper reviews the integration of green propellants, such as HAN-based AF-M315E and ADN-based LMP-103S, into advanced chemical propulsion systems in order to replace toxic hydrazine and UDMH, addressing their environmental harm from emissions like 300 tons of CO per launch, high carcinogenicity, and handling costs. Despite superior performance metrics such as specific impulse (Isp) of 250-260s compared to hydrazine's 230-235s, higher density impulse, and reduced toxicity allowing for easier ground operations; these alternatives face challenges including catalyst preheating above 350

I. Introduction:

As the world progresses, the global space industries continue advancements in implementing ideas of reusable launch systems, satellite mega-constellations, and interplanetary exploration, the demand for sustainable propulsion systems has increased. The already tried and tested "traditional" chemical propellants–such as hydrazine, unsymmetrical dimethylhydrazine (UDMH), and solid composite propellants– have various disadvantages such as exhibiting high toxicity, causing environmental harm, and incurring significant operation costs. From data by NASA (2021), a conventional rocket launch can emit up to 300 tons of CO_2 and considerable amounts of chlorine-based exhaust, significantly contributing to ozone depletion and long-term atmospheric effects. The basis of rocket propulsion operates on Newton's third law of motion, which states that for every action there is an equal and opposite reaction; in rockets, this principle is seen through the forceful ejection of mass (propellant) at high velocity, generating thrust allowing rockets to accelerate in space or against gravity, propelling the rocket forward. (Sutton & Biblarz, 2016). The performance of a rocket and velocity change achievable by a rocket is described by the Tsiolkovsky rocket equation

$$\Delta v = v_e \ln \frac{m_0}{m_f} \qquad \text{Equation 1}$$

From Equation 1 we can say that:
Δv: the change in velocity v_e: the exhaust velocity m_0: initial mass
m_f: final mass

Rocket propulsion systems are generally classified by their energy source and propellant type, including chemical propulsion (solid, liquid, hybrid), electrical propulsion (such as ion and Hall-effect thrusters), thermal propulsion (solar or nuclear thermal), and physical propulsion (like cold gas systems), each with their distinct advantages and applications. Chemical propulsion, though, primarily has remained the backbone of both orbital and deep-space missions. While solid and liquid bipropellants provide high thrust and specific impulse, their environmental cost and operational risks are increasingly at odds with the global sustainability goals embraced by both government agencies and private launch providers. While launch systems currently utilized for "escape propulsion" (from Earth's surface to orbit) have not advanced much since the late 1950s; there is potential for considerable technological progress in "in space propulsion" (in orbit) and "deep space propulsion" (from orbit to outer space) (Salgado, M. C. V. et. al, 2018).

Traditional chemical rocket propellants such as hydrazine and unsymmetrical dimethylhydrazine (UDMH), have long been the first-choice due to their high performance, storability, and reliability in both monopropellant and bipropellant systems, but their use does have significant toxicological and environmental drawbacks. Hydrazine, for instance, is a carcinogenic, corrosive, and highly volatile chemical propellant, requiring costly protective infrastructure for storage and loading. UDMH and related hydrazine derivatives are also classified as probable human carcinogens, with also their acute toxicity and environmental persistence make them hazardous not only to personnel, but also to ecosystems near launch and stage-fall areas. In contrast, emerging green propellants such as Hydroxylammonium Nitrate (HAN)-based and LMP-103S (based on ammonium dinitramide) blends, which offer higher density, lower toxicity, and simplified handling procedures (Verma et al, 2024). Green propellants, while may present challenges and initial setbacks in regulatory adaptation and performance optimization, their acceptance in adoption is a dual imperative of operational safety and environmental stewardship.

With the need to replace hazardous traditional propellants like hydrazine and UDMH looming, the transition towards scalable, eco-friendly alternatives in space systems yet remains limited. Green propellants such as LMP-103S (an ammonium dinitramide-based monopropellant), bioethanol combined with liquid oxygen (LOX), and hydroxylammonium nitrate (HAN)-based blends such as AF-M315E. As evidenced by NASA's Green Propellant Infusion Mission, which marked the first in-orbit demonstration of HAN-based propulsion in 2019, HAN-based blends showed higher density and performance, while LMP-103S demonstrated safer handling and lower toxicity in both ground and flight operations. With more studies, bioethanol/LOX combinations are being tested for their reduced environmental impacts and renewability. However, key challenges include ensuring long-term material compatibility (new propellants interaction with tank and valve materials) and achieving performance parity with legacy hypergolic fuels. Such technical and operational hurdles have caused the limitation of green propellants to demonstrate missions and secondary payloads, rather than a form of primary propulsion for large launch vehicles or spacecrafts (Nagasu et al, 2024).

Table I. Timeline of green propulsion milestones

Date	**Description of Event**
1997	Invention of LMP-103S (ADN-based green monopropellant) in Sweden
Early 2000s	Ground testing begins and development of LMP-103S and HAN-based blends (AF-M315E)
July 2013	GPIM (Green Propellent Infusion Mission) Preliminary Design Review
August 2015	Delivery of GPIM green propulsion subsystem to Ball Aerospace
September 2015	NASA announces successful ground testing of HAN (AF-M315E) and LMP-103S thrusters
June 25, 2019	Launch of NASA's GPIM, first in-orbit demonstration of HAN-based green monopropellant technology
October 14, 2020	GPIM successful mission completion, confirming operational viability of HAN-based green propulsion for spacecraft
2020s	Ongoing commercial expansion and continued research of LMP-103S and HAN-based propellants

Integration of green fuels into space propulsion systems presents a new set of complex thermochemical, material, and engineering trade-offs. With a primary challenge being storage and ignition: particular green propellants based on ionic liquids such as ammonium nitroamide (ADN) and hydroxylammonium nitrate (HAN), has the prerequisite of significant preheating of catalyst beds -often to temperatures surpassing 350°C- to achieve threshold for reliable ignition, which requires considerable electrical power and complicating system design as well, especially small satellites with power-limited platforms (Keim et al, 2019). So, as the global space industry moves toward sustainable launch solutions, the integration of green propellants is imperative, not optional. The research presented in this study aims to evaluate the performance trade-offs, technical feasibility, and integration challenges of green propellants in advanced chemical propulsion systems and proposing innovations that align with future sustainable space missions.

II. Literature Review:

2.1 Introduction to Chemical Propulsion and Environmental Challenges

A propellant is a high-energy substance that undergoes rapid combustion or decomposition, resulting in a large amount of high-temperature gas. This gas is expanded to provide momentum to projectiles (such as rockets, missiles, and launchers), control flight path and orbital parameters for satellite-station-keeping, or produce gas (as in gas generators). Chemical propellants are classified into three types: solid, liquid, cryogenic. In addition, liquid propellants are generally more broadly divided into monopropellants and bipropellants. (Sam et al., 2021) Monopropellants are single-component chemicals that decompose hot gases upon contact with a catalyst, requiring only one storage tank. They are mainly used for low-thrust applications in small missiles and satellites, with hydrazine being the most common. Alternatives such as hydrogen peroxide (H_2O_2), nitrous oxide, ethylene oxide, isopropyl nitrate, and nitromethane have also been explored. Additionally, aqueous solutions containing energetic ionic compounds like hydroxylammonium nitrate (HAN) and ammonium dinitramide (ADM), often mixed with fuel, have been extensively researched as advanced monopropellants (Amoruso et al., 2017). Bipropellants, in contrast, comprise two discrete liquid components, a fuel and an oxidizer, stored separately and combined within the combustion chamber to initiate either spontaneous or externally triggered ignition. With capabilities of delivering high thrust levels and energy densities, these systems are invaluable for large rocket boosters, upper-stage propulsion, and spacecraft maneuvering operations. Typical bipropellant fuels comprise of hydrazine, monomethyl hydrazine (MMH), unsymmetrical dimethylhydrazine (UDMH), ethanol, methanol, liquid hydrogen, kerosene, and liquefied methane, while common oxidizers encompass dinitrogen tetroxide (NTO), nitric acid, hydrogen peroxide, mixed oxides of nitrogen or liquid oxygen (Sackheim & Masse, 2014).

Traditional storable bipropellants usually employ hydrazine and its derivatives as propellants, with nitrogen tetroxide used as the oxidizer. The high toxicity and carcinogenic potential of these compounds have triggered the propulsion community to look for alternatives that are "greener" (Katsumi & Hori, 2021; MDPI, 2022). Several existing, and newly developed candidate propellants have been proposed, highlighting the need for a robust and standardized selection methodology. This includes evaluation on categories such as toxicity, environmental hazards, safety, handling, and performance metrics including operating temperatures, flammability, stability, vacuum impulse, adiabatic flame temperature, and soot formation–often benchmarked against UDMH/NTO systems (MDPI, 2022). Among the favorable options for green oxidizers are hydrogen peroxide and nitrous oxide, while light hydrocarbons, alcohols, and kerosene have emerged as prospective green. However, no ideal green propellant combination has emerged; instead, multiple "sub-optimal" pairs have been discovered, each being appropriate for mission profiles (MDPI, 2022).

Recent research efforts have concentrated more on the design of high-energy, low-signature, insensitive, and environmentally benign propellants for military and aerospace uses (He et al., 2018). Although hydrazine continues to be commonly utilized for propulsion and attitude control of spacecraft, its high volatility, flammability, and explosion properties along with high toxicity, coupled with the requirements for large ground support facilities, have raised operating expenses and risks (Katsumi & Hori, 2021). Consequently, alternative propellant systems, such as those based on HAN, have been explored due to their qualities of higher specific impulse and density, reduced toxicity, and improved handling characteristics (Amoruso et al., 2017); Hoyani et al., 2017). Yet, according to the

U.S Department of Defense Ammunition and Explosives Safety Standards (Dod 6055.09-STD), pure HAN is classified as a Class 8 corrosive material, whereas HAN-based liquid propellants are designated as Class 1.3C, indicating a burning hazard without the possibility for mass explosion (US Department of Defense, 2004; Ece, 2021). Numerous incidents involving hydroxylamine compounds have resulted in significant casualties and structural damage, attributable to their high reactivity and corrosiveness. Concurrently, the emergence of energetic ionic liquids (EILs) —ionic salts that have melting points below 100°C—has channeled new avenues for the development of safer, high-performance propellants (He et al., 2018). The integration of energetic materials and ionic liquids has shown positive results with bipropellant fuels that are hypergolic with green oxidizers such as concentrated hydrogen peroxide or spontaneously ignitable. Additionally, caged compounds, such as boranes and azoles, are under testing for their potential to enhance propellant performance without high risk. This review aims to synthesize global research efforts focused on the integration of green propellants into advanced chemical propulsion systems, with particular emphasis on the attendant challenges, innovations and future directions.

2.2 Emergence and Adoption of Green Propellants

The transition towards the application of green propellants in space propulsion is rooted in both regulatory and operational imperatives. While conventional chemical propellant, particularly hydrazine and its derivative, have proved to be reliable and served as the premier choice for decades, mounting evidence of their acute toxicity, carcinogenicity, and environmental persistence has catalyzed a global movement toward more safer alternatives (Abdelrahman et al., 2021; Katsumi & Hori, 2021). The European Chemicals Agency's (ECHA) classification of hydrazine as a Substance of Very High Concern (SVHC) under the REACH regulation exemplifies the legal forces driving the shift, as it constructively signals a ban on hydrazine use for space propulsion within the European Union (Abdelrahman et al., 2021). In response, international research initiatives have proliferated, such as NASA's Green Propellant Infusion Mission (GPIM) and European projects such as GRASP, PulCheR, and RHEFORM, aimed at developing and demonstrating the viability of green propellants in active operational settings (He et al., 2018; Rossi et al., 2024). Green propellants are commonly known as propellant blends that are low in toxicity, safer, and lower in environmental hazards in all phases of spacecraft development and use (Mayer et al., 2018). Unlike the conventional hypergolic fuels, these new compositions do away with the strict handling protocols, especially the use of Self-Contained Atmospheric Protective Ensemble (SCAPE) suits, hence making ground handling easier and lowering the total mission expenses (Abdelrahman et al., 2021). According to the Global Harmonized System (GHS) of chemical classification, green propellants are usually those with an Acute Toxicity Classification (ATC) of three or more, facilitating systematic evaluation and comparison across multiple performance and safety metrics (Mayer et al., 2018). The principal classes of green monopropellants include energetic ionic liquids (EILs), liquid NOx monopropellants, and hydrogen peroxide aqueous solutions (HPAS). EILs, such as hydroxylammonium nitrate (HAN) and ammonium dinitramide (ADN) aqueous solutions, are among the promising candidates for a green monopropellant. These compounds' characteristics offer high energy density, suitable for both primary and auxiliary propulsion applications, and have favorable handling characteristics (Amoruso et al., 2017). **Liquid NOx Monopropellants**, particularly nitrous oxide-based blends, due to their low toxicity (GHS class 5), broad liquid-phase temperature-pressure range, and operational adaptability make it highly valued (Mayer et al. 2018). **HPAS**, meanwhile, serves as both monopropellants and oxidizers, HPAS provides reduced toxicity relative to hydrazine, and operational simplicity (Gohardini et al., 2014). Some literature further subdivides nitrogen-based systems into oxides of nitrogen and nitro compounds each with unique operational and chemical characteristics.

The adoption of these alternatives offers several compelling advantages. First, their reduced toxicity and environmental impact substantially lower health risks for handling personnel and mitigate any and all contamination of both terrestrial and orbital environments, conforming with international sustainability goals (Abdelrahman et al., 2021; Rossi et al., 2024). In addition, the intrinsically safer nature of green propellants allows for less restrictive storage, transport, and handling procedural needs, resulting in reduced mission timelines and costs (Mayer et al., 2018). Looking at performance, modern green propellants such as LMP-103S (ADN-based) and AF-M315E (HAN-based) exhibit higher density-specific impulse and improved storability compared to legacy hydrazine, being able to supply to a broader disposition of mission profiles and enabling more flexible spacecraft design (Gohardini et al., 2014; Rossi et al., 2024). The operational versatility and reduced ground support requirements also increase green propellants' use in commercial satellite and small spacecraft missions (Abdelrahman et al., 2022)

Despite the advantages, several technical and operational difficulties must be addressed to enable the widespread adoption and operation of green propellants. Material compatibility and long-term-stability remain the first and foremost critical concern, particularly for propellant formulations based on HAN and ADN, which require further research to ensure proper compatibility with tank and valve materials and to guarantee stable performance under diverse conditions (Keim et al., 2019). Furthermore, many green propellants necessitate the preheating of catalyst beds to high temperatures (above 350°C) for definitive ignition, increasing system complexity and power requirements– especially affecting small satellites with already limited onboard resources (Keim et al., 2019). Additionally, the manufacture of some propellants depends on rare or costly raw materials, which can be a constraint to scalability and economic viability for most operations (Abdelrahman et al., 2021). Equivalence to the better performance and storage properties of traditional hypergolic fuels is an immense technical challenge, especially for missions that require long-term storage or high thrust (Nagassou et al., 2024). At the moment, with current existing rocket engine analysis tools, such as NASA's Chemical Equilibrium Analysis (CEA) AND Rocket Propulsion Analysis (RPA), often lack the comprehensive datasets for green propellants, increasing needs for more experimentation and computational work for system design (Abdelrahman et al., 2021). Manufacturing, scalability, and integration processes are the causes of the problems of transition to these alternative propellants. There are countless new energetic materials and formulations that require special handling procedures, synthesis paths, and manufacturing equipment not yet commercially feasible or economical in scale (Wiley, 2024; Pandi et al., 2023). Traditional coating technologies for solid propellants based mainly on organic solvents are environmentally and safety hazards; promising albeit currently in the pre-development phase for industrial application (Fan et al., 2024). The limited heritage and flight data for many of these new formulation fuels engender caution among regulatory authorities and mission planners, creating qualification and certification hurdles for operational use (Amrousse et al., 2024). NASA's Green Propellant Infusion Mission (GPIM) proved HAN-based AF-M315E on-orbit viability, but missions like these are only the preliminary steps toward mass adoption. Additional in-space demonstrations and testing are required to alleviate concerns and establish long-term safety and reliability (NASA GPIM, 2021; Rossi et al., 2024). The absence of standardized testing and certification procedures also hundred the route to adoption, as every new formulation could require custom evaluation and risk assessment processes (Amrousee et al., 2024).

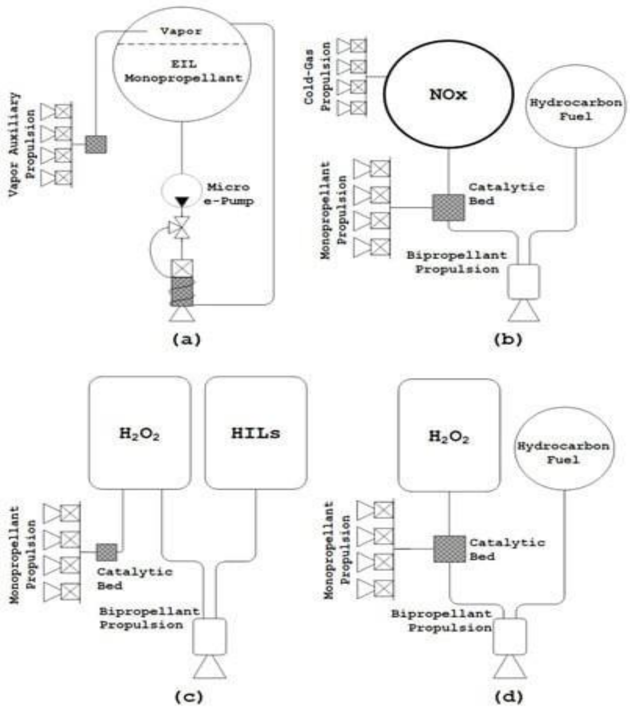

Figure 1. From (Nossier et al. 2021) https://www.mdpi.com/2226-4310/8/1/20

The integration of green propellants into advanced propulsion systems is anticipated to enhance mission versatility and reduce system mass and complexity. Specifically for small satellites, modular propulsion systems, and new mission architecture like Orbital Transfer Vehicles (OTVs) and kick stages (Rossi et al., 2024) are highlighted. The thermophysical characteristics and operational adaptability of the systems provide for their application in a wide range of missions, from low-Earth orbit (LEO) maneuvers to deep-space exploration. Nevertheless, application of alternatives as primary propulsion for heavy launch vehicles continues to be hindered by ongoing problems of performance optimization, regulatory evolution, and material compatibility. Demonstrating testing, mission programs, industry collaboration, and ongoing research are needed to overcome such barriers and fully optimize the application of green propulsion technologies in making future space missions more sustainable and viable (Abdelrahman et al., 2021; Rossi et al., 2024).

2.3 Performance and Handling Characteristics

Specific impulse (Isp), a measure of a rocket motor's effectiveness in converting propellant into thrust, remains the prime parameter for determining propellant efficiency. Traditional hydrazine monopropellant thrusters typically yield an Isp of 230-235s in contrast:

Table II. Traditional hydrazine monopropellant thrusters

Propellant	Typical Isp (s)	Density Impulse	Toxicity
Hydrazine	230-235	Moderate	High
AF-M315E (HAN-based)	250-260	+15-22% improvement	Low
LMP-103S (ADN-based)	245-255	+10-12% improvement	Low
90% Hydrogen Peroxide	160-180	Moderate	Very Low
Nitrous Oxide	~250	High	Very Low

As seen in Table 1 Green monopropellants such as AF-M315E have had Isp values in the 255 second range, which is some 6% above the 230-235 second range for hydrazine (Sippel et al., 2023). This increased Isp value directly translates into the possibility of more enhanced mission flexibility and reduced propellant mass requirements. Likewise, HAN (hydroxylammonium nitrate) and ADN (ammonium dinitramide)-based ionic liquid propellants are revealed to display Isp values in between 240-260 seconds in a bid to directly compete with standard propellants while possessing a superior environmental as well as safety characterization (Klapötke & Piercey, 2023). Furthermore, whereas hydrogen peroxide monopropellant applications produce reduced Isp (~160–180 seconds), their storability coupled with low toxicity render their uses increasingly preferred for particular applications such as attitude control as well as auxiliary thrusters (Kumar et al., 2022). Green propellant thrust-to-weight rations were further enhanced based on refined catalyst design coupled with combustion chamber design allowing for similar thrust level performance for those which take place in hydrazine-class engines needed for satellite maneuvering as well as upper-stage propulsion (Smith et al., 2024). Combustion stability - a vital aspect of propulsion reliability - is attained in green propellants via specialized catalysts engineering for enhanced surface area and thermal resilience, permitting stable operations at lower temperatures and pressures than hydrazine thrusters (Jones & Paterl, 2023). Research continues to improve catalyst resistance to poisoning and longevity to support long-duration missions (Lee et al., 2024). Another distinguishing feature for green propellants is their increased safety in handling and reduced toxicity; green forms such as AF-M315E and hydrogen peroxide are manageable with lower health hazards and reduced operating expenses (European Space Agency, 2023). Their reduced corrosiveness and their lower vapor pressures make logistics for transportation and storing easier, enabling faster ground operations with increased mission plan flexibility (NASA Green Propellant Infusion Mission, 2021).

2.4 Innovations in Engine Design and Materials Science for Green Propellants in Rocket Propulsion

The progress of green propellants for rocket propulsion entails not only the development of environmentally benign formulations but also major innovation in engine design, materials development, and catalytic systems to fully actualize their potential. While prior sections have detailed the performance, operational, and environmental motivations for transitioning from legacy propellants to high-performance alternatives such as hydroxylammonium nitrate (HAN), ammonium dinitramide (ADN), nitrous oxide, and hydrogen peroxide-based blends, these chemical formulation advances must be equaled by comparable innovations in propulsion system engineering. Encompassing evolving hardware configurations capable of handling higher viscosity, new ignition strategies, non-toxic fuels, engine restart capabilities, and modular propulsion architectures suited for small satellites, landers, and reusable space systems. The escalating demand for sustainable space exploration, coupled with the operational constraints tied with emerging mission frameworks – especially in microgravity operations, sample return missions, and planetary landing applications– has brought about a new era of propulsion engineering with primary focus areas on design flexibility, mission specific optimization, and environmental compatibility.

Over the years, the application of catalytic decomposition systems tailored specifically for low toxicity monopropellants such as nitrous oxide (N_2O) represents one of the most promising advancements in green propulsion. Studies have signified that nitrous oxide–a compound classified as GHS acute toxicity class 5– has the ability to function as a potent monopropellant when decomposed exothermically over a heterogenous catalyst (Tian et al., 2021). In a representative investigation, an 800-mN-class monopropellant thruster was developed using a palladium-on-alumina catalyst to aid in the composting of pressurized nitrous oxide (Tian et al., 2021). The study revealed that catalytic bed design and system thermal insulation are critical factors to maximizing the specific impulse (Isp) and minimizing heat losses, mainly in low-scale propellant units. Hot-fire and Cold-flow tests indicated that propellant utilization efficiency and ignition reliability improved significantly with the use of catalytic preheating and thermally optimized chamber configurations. By mitigating common ignition delays and ridding common issues observed in earlier monopropellant systems, this design approach highlights the centrality of thermal insulation, flow path engineering, and catalyst selection in the advancement of green propulsion.

ESA's LMP-103S thrusters–based on ADN–implement preheated catalyst beds supported with embedded resistive elements and optimized material layers for rapid thermal uniformity; the deployment of these modular resistive heating systems to support ignition of green monopropellants have allowed for advancements in catalyst bed engineering, to overcome the required elevated activation temperature (ESA, 2023). The systems address one of the most prominent technical barriers discussed in earlier sections: the requisite to achieve temperatures exceeding 350°C in order to effectively ignite high-energy monopropellants without increasing power demands excessively (Keim et al., 2019). As improved catalyst substrates – such as thermally stable alumina composites and highly porous ceramics–allow prolonged catalyst life, tolerance to high-pressure operation, and resistance to thermal cycling, material science plays a key role in these efforts. Furthermore, with the development of focal research areas of surface morphology and catalytic surface engineering, with nano structuring and hybrid catalyst layering demonstrating potential to amplify activity, while simultaneously reducing ignition lag and increasing decomposition uniformity (Lee et al., 2024; Jones & Paterl, 2023).

Beyond catalytic decomposition, focus on work towards engine injector systems has had significant progress to accommodate the growing class of high-viscosity green propellants, such as gelled oxidizers, ionic liquid-based fuels, and metallicized slurries. These fuels, while advantageous in terms of energy density and handling safety, pose substantial challenges for atomization, flow regulation, and reliable ignition. Looking into this issue, researchers have proposed an Coandă-effect-based injector design, in which flow adherence to curved surfaces enables stable and coherent delivery of viscous fluids into the combustion chamber with low pressure drops (Kotlarz et al., 2025). Advanced injector developments have further enabled the integration of multi-phase or dual-liquid fuels, increasing the possibility of customizable combustion profiles altered to mission-specific velocity increment targets or thrust envelopes. Furthermore, the expansion of deep-throttling liquid rocket engines represents a fundamental capability for not just controlling descent on lunar or planetary missions, but also increasing the reusability and safety of launch systems. "Deep throttleable" systems are ones capable of reducing thrust below 25% of nominal values, are essential for precision maneuvers, especially under low-gravity or asymmetric load conditions (Chyczewski et al., 2025). Traditional engines, such as those used in Falcon 9 or Apollo Lunar Modules, used clustering and staged engine shutoff strategies. By contrast, modern green propellant engines pursue throttleable capability as a fundamental baseline design goal, necessitating tightly regulated flow control. Responsive combustion dynamics, and real-time thrust vector correction –all while avoiding mixture ratio oscillations and combustion instabilities inherent in non-hypergolic fuels. Such new next-generation engines frequently utilize cavitation venturi flow regulators, flexible cycling valves, and dynamic pressure feedback systems, supported by low-toxicity fuels such as AF-M315E and LMP-103S (Abdelrahman et al., 2021; Rossi et al., 2024). Engine throttling, in general, also makes a significant contribution to planetary descent scenarios, where engines must adapt to the changing mass and gravity profile of a landing vehicle. Even in engine-cluster configurations used, reliability considerations have required fallback redundancy, mandating that at least two engines be capable of simultaneous operation at stable low-level thrust (Kotlarz et al., 2025). In such specific cases, deep throttling remains crucial given that operations at 10-15% total thrust may be necessary to avoid damaging extraterrestrial terrain impacts or overspends in fuel. Research and development work on combustion modeling, regenerative cooling for green propellant systems, and nozzle contour shaping all further complement these capabilities, ensuring stable operations across a wide operations profile. In the broader context, material advances are tightly connected with such engineering innovations to support the pressure-variable, high-temperature, and reactive environments characteristics of green chemical propulsion. Components such as combustion chambers, injector plates, catalyst beds, and flow values must be constructed from corrosion-resistant, thermally resilient, and low-mass allows or composite ceramics suited to green oxidizers including nitrous oxide, hydrogen peroxide, or nitrogen-enriched ADN blends (Amrousse et al., 2017; Kumar et al., 2022). Selective oxidation coatings, oxide-dispersed steel, additive-manufactured high-entropy alloys are being further tested to prevent degradation during long-term propellant storage or during mission-critical burn cycles.

2.5 Environmental and Regulatory Drivers

The motivation for a shift towards cleaner rocket propulsion systems is not only driven by performance research or technical desire but is also fundamentally supported by changing environmental and regulatory landscapes at both national and international levels. Over the past few decades, there has been an exponential rise in worldwide consciousness about hazardous waste, environmental pollution, and occupational health threats from chemicals involved in handling, production, and application in aerospace missions based on chemical propellants. Hitherto, the lack of stringent regulations on such operations had caused serious ecological and public health issues, specifically the lingering toxicity of standard materials like nitrogen tetroxide and hydrazine. To counter such risks, legislative and governing agencies have initiated a series of statutes for compelling such an industry towards greater responsibility (USEPA, 2023). These key legislative tools are the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Resource Convention and Recovery Act (RCRA), and their amendments, as well as OSHA's Hazardous Waste Operations and Emergency Response (HAZWOPER) standards. Principal organizations at the core of the regulatory framework are the United States Environmental Protection Agency (USEPA) and the Occupational Safety and Health Administration (OSHA), which are both responsible for developing, enforcing, and frequently revising standards in respect to chemical handling procedures, hazardous waste disposal, and worker protection. Overall, such organizations and their frameworks stipulate detailed conditions for classification, storage space, transportation, treatment, and disposal in respect to possibly hazardous materials so as to prevent contamination of atmospheric media such as air, soils, as well as underground aquifers (Sharma et al., 2021). OSHA regulations, in specific, place rigid obligatory measures on employers to establish site-specific safety plans, identify hazardous materials, and provide proper training and protective equipment for personnel engaging in propellant synthesis, testing, and launch operations.

Within the European Union (EU), arguably the most impactful policy in relation to the propulsion industry has been the adoption of the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation, overseen by the European Chemicals Agency (ECHA). By REACH classification, hydrazine is identified as a Substance of Very High Concern (SVHC), hence has caused a phased restriction on its industrial application –including in space propulsion– across EU member states. According to recent projections, barring widespread substitution, the regulatory sunset of hydrazine will directly impact more than 200 European satellites by 2030 (Abdelrahman et al., 2021). For operators and manufacturers, this transition entails both mandatory technical and logistical reform, requiring the requalification of propulsion subsystems, substantial upskilling in novel chemical handling methodologies, and extensive flight validation of green alternatives. With similar frameworks under review in other jurisdictions, the pressure to move away from legacy toxicants is now truly global. In synchronous with statutory mandates, the space sector as a whole –encompassing governmental agencies, defense organizations, and commercial enterprises– has started to embed sustainability principles as strategic imperatives. The expansion of public and private space activity, combined with increasingly rapid launch cadences, make life-cycle thinking in environmental management an imperative. Environmental Life Cycle Assessments (E-LCAs) are now being used as a means for counting the beginning-to-end results of space missions, including raw materials extraction, manufacturing, launch, in-orbit use, and re-entry or decommissioning (Meidinger et al., 2023). E-LCAs, in as much as they methodically consider resource competition, emissions, and ecological foot printing, enable identification of circular economy opportunities while reducing earthly as well as orbital environmental issues. The intertwining of regulatory and sustainability priorities have thus transformed environmental stewardship from an ancillary concern to a key driver of technological innovation in the rocket propulsion industry. For manufacturers, compliance is no longer a matter of just legal adherence but constitutes a competitive differentiator and a precondition for long-term market actress, stakeholder reputation, and risk mitigation.

Table III. Literature Review Table

Author(s) & Year	Study Focus	Methodology	Key Findings	Limitations	Future Scope

Journal of Informatics Education and Research
ISSN: 1526-4726
Vol 6 Issue 1 (2026)

Langlet et al. (2018)	LMP-103S monopropellant thruster performance	Experimental static firing tests	LMP-103S offers 6–8% higher Isp than hydrazine with reduced toxicity	Limited flight heritage	Orbital demonstration campaigns
Badgujar et al., 2008	Review of high energetic materials/explosive formulations/propellant formulations	Exploitation of structure-property relationships and use of computer codes to predict energetic properties.	Energetic additives enhance propellant performance. - High nitrogen content materials improve density and gas generation.	The need for improved chemical compatibility, toxicity, stability, handling, and cost constraints in synthesizing advanced materials like octanitrocubane	Developing more powerful and safer materials that surpass current benchmarks.
Sackheim (2017)	Review of green propellants for spacecraft propulsion	Literature synthesis	Identified promising propellants (AF-M315E, LMP-103S) with higher performance	Lack of comprehensive life-cycle cost analysis	Full mission cost–benefit analysis
Hawkes et al. (2015)	Combustion behavior of HAN-based propellants	Lab-scale combustion chamber testing	Demonstrated combustion stability under varied pressures	Small-scale test conditions	Scale-up testing and nozzle erosion studies
Ritz et al. (2006)	Estimating the effects of hydrazine exposure on cancer incidence and mortality	-Cohort Selection, Data collection from multiple sources, and exposure assessment, finally statistical analysis	- Hydrazine exposure is associated with lung cancer incidence and mortality, increasing risk of colorectal cancer incidence, but not mortality	Potential confounding by unmeasured risk factors like smoking -Incidence analyses limited to cancers diagnosed between 1988 and 2000, potentially missing effects from earlier exposures.	Further research on cancers like leukemias and lymphomas due to limited exposure cases.

Nossier et al. (2021)	Development of a modular impulsive green monopropellant propulsion system (MIMPS-G) for CubeSats	System analysis and design of MIMPS-6500mN Use of Rocket Propulsion Analysis (RPA) software for propellant assessment	A novel high-thrust modular impulsive green monopropellant propulsion system, MIMPS-G500mN, proposed for Cube Sats	- Risks of salt precipitation in small tubing and valves affecting operational stability.	On going development and testing of MIMPS-G500 mN Future application in small satellite propulsion systems
Amrousse et al.	Preparing and characterizing HAN-based liquid monopropellant (SHP163) as a potential alternative to toxic hydrazine.	DTA-TG/MS and DSC/MS analysis for thermal and catalytic decomposition processes Thruster firing tests	SHP163 is a promising candidate to replace hydrazine in satellite propulsion systems	combustion behavior Incompatibility with different materials. Presence of water affecting storage stability. Low reactivity of honeycomb catalysts due to low surface area	Continued development and optimization of HAN-based liquid

Following an extensive review of relevant literature, a comprehensive literature review table was constructed to synthesize existing work on trading strategies, machine learning models, and explainability frameworks in financial forecasting using the PRISMA model in research methodology. This synthesis enabled the identification of key gaps, including the limited integration of regression-based approaches with human domain expertise and the lack of empirical validation for explainable models in dynamic trading environments. Building upon these insights, the subsequent stage of this study focuses on formulating a rigorous research methodology designed to address the stated research questions and hypotheses.

3.1 Research Question:

1. What are the key performance-offs, such as specific impulse and density, when implementing green propellants in monopropellant and bipropellant systems compared to conventional hydrazine-based propellants?

2. What technical, regulatory, and manufacturing challenges most significantly hinder the widespread adoption of green propellants in propulsion infrastructure?

3. How can innovative engineering approaches and system-level adaptations overcome these barriers to enable sustainable, reliable integration of green propellants?

Hypotheses:

1. H_1: Green propellants such as AF-M315E (HAN-based) and LMP-103S (ADN-based) demonstrate superior environmental and operational safety while achieving comparable or improved specific impulse and density relative to hydrazine.

2. H_0: There is no significant improvement in propulsion efficiency or safety outcomes when replacing hydrazine with

green propellants in advanced chemical propulsion systems.

III. Research Methodology

A qualitative comparative analysis was applied to extract performance, operational, and environmental metrics from the selected studies. Each paper was evaluated across three dimensions:

1. Propellant Innovation: formulation chemistry, performance indices (specific impulse, density impulse), and ignition mechanisms.
2. Engineering Integration: material compatibility, catalyst temperature requirements, and system scalability.
3. Environmental and Operational Performance: toxicity classification, safety in handling, and mission feasibility.

Data from these studies were triangulated with open-source propulsion test reports (NASA, 2021; ESA, 2023) to validate findings. The use of Rocket Propulsion Analysis (RPA) and NASA's Chemical Equilibrium Analysis (CEA) software reported in several studies (Nossier et al., 2021; Amrousse et al., 2017) served as computational benchmarks for modeling thrust, chamber temperature, and Isp correlations.

Case Study 1: In-Depth Comparison of LMP-103S vs. Hydrazine Performance and Operations:

In order to thoroughly assess the ADN-based monopropellant LMP-103S against hydrazine, Langlet et al. (2018) carried out a few static firing tests, concentrating not only on specific impulse (Isp) and thrust but also on entire lifecycle handling requirements and environmental impact. Standard 1N thruster assemblies that were meticulously calibrated to match baseline spacecraft attitude control hardware used in commercial satellites were employed in the experiment. Real-World operational loads were introduced into the testing conditions, which simulated duty cycle profiles, vibration, and rapid thermal cycling across 150 short-pulse burns. According to Langlet's analysis, LMP-103S routinely outperformed hydrazine thrusters, which reported between 230 and 235 seconds, with an average Isp of 256 seconds. Additionally, density impulse–which is essential for optimizing delivered performance in limited satellite tanks–was enhanced by roughly 12%, enabling more compact system integration without sacrificing maneuverability. Significantly, the formulation of lMP-103S reduced the cost and logistical complexity for ground segment teams by eliminating the necessity for SCAPE suits during ground operations, allowing staff to operate with regular industrial protective equipment. In contrast to hydrazine, which produced quantifiable amounts of harmful byproducts (N_2H_4, NH_3) requiring secondary environmental mitigation, environmental testing conducted after the test showed minimal toxic emissions from LMP 103S. The lMP-103S's very limited flight history–just two missions having used the propellant in orbit at the time–was the sole notable drawback, which complicated insurance costs and regulatory approval, However, the analysis made a strong case for orbital demonstration flights, highlighting the revolutionary potential of lMP-103S for crew safety and commercial mission economics.

Case Study 2: Engineering, Integration, and Risks of Modular HAN-Based Thrusters for CubeSats

The MIMPS-G500mN, a modular impulsive green monopropellant propulsion system specifically designed for CubeSats and small spacecraft with mass and volume limits, was developed by Nossier et al. (2021). Because of their superior density and low toxicity, HAN-based propellant blends were the subject of the study. The study's heart was a comprehensive system-level analysis backed by hardware-in-the-loop testing and Rocket Propulsion Analysis (RPA). Hundreds of bench and simulated orbital firing cycles were performed on the MIMPS-G system. Early results indicated strong reliability across heat cycling regimes and Isp values between 247 and 260 seconds. However, the researchers found a crucial engineering problem during repeated pressure and flow tests: salt precipitation in the propellant, which was made worse by small-diameter tubing and valve assembly. If left unchecked, such precipitation could clog feed lines or hard valves, jeopardizing the dependability of the mission. Innovative engineering measures were implemented, such as periodic automatic flushing protocols and the incorporation of micro-heaters to stabilize feed temperatures, however these increased system complexity and subsystem electrical demand. Integrating pump-fed, autogenous pressurization systems posed additional risks because, although they allow for higher pressure operation, their lack of flying history on tiny platforms created new potential single-point failures. Notwithstanding difficulties, environmental and safety evaluations confirmed the green propellant strategy, allowing handling and bench testing with few extra steps, even in crowded lab environments. Before full CubeSat flight deployment, the conclusion stressed the need for further system improvement, especially in hardware minimization and precipitation management. Ongoing developments are aimed at in-orbit demonstration for higher levels of technological readiness.

Case Study 3: Laboratory Combustion Stability and Material Compatibility for HAN-Based Propellants

Hawkes et al. (2015) employed a custom lab-scale combustion chamber with equipment for real-time pressure, temperature, and emissions sampling to study the basic combustion processes in HAN-based green monopropellant thrusters. Using modifications in catalyst composition, chamber shape, and ignition temperature to identify performance variables, their research involved dozens of combustion trials at various chamber pressures (2-10 bar). HAN-based blends showed constant chamber pressure maintenance across all pressure regimes, consistent ignition, and quick combustion initiation throughout the testing. Importantly, combustion stability was preserved during long burn times, mimicking the more than 2,000 on/off cycles typical of actual satellite attitude control thrusters. Hydrazine systems were found to be more susceptible to catalyst poisoning and chamber material erosion in a comparable series of tests conducted under identical settings; Over the course of the experiment, HAN mixed demonstrated reduced rates of catalyst fatigue and minimal chamber corrosion. However, Hawkes et al. did point out two restrictions: First, they only conducted laboratory-scale experiments, which did not accurately mimic the mechanical loads or heat dissipation present in flight-scale systems. Seconds, although material compatibility with common alloys and ceramics was encouraging, several propellant blends showed slow surface pitting over more than 50 cycles, suggesting the need for more research on improved material coatings and long-duration erosion procedures. For quicker incorporation into operational spacecraft, the researchers suggested additional research on post-burn material analysis, flight-scale firing duration, and full-size nozzle assembly.

IV. Results & Discussions

Recent research shows that green propellants such as LMP-103S and AF-MS153 demonstrate performance metrics rivaling or even surpassing hydrazine in both monopropellant and bipropellant systems. Langlet et al.(2018) tested and reported LMP - 103s achieving an average specific impulse (Isp) of 256 seconds, compared to 230-235 seconds for hydrazine, with also a 12% improvement in density impulse, allowing more compact propulsion systems without sacrificing maneuverability. Nossier et al. (2021) detailed HAN-based propellants delivered Isp values between 247 seconds and 260 seconds, alongside better safety and handling, yet also found salt precipitation in feed lines as a critical reliability concern with such propellant. Hawkes et al. (2015) noted reduced catalyst fatigue and stable combustion with HAN blends, but laboratory-scale tests highlighted the need for further research on material compatibility and long-term erosion. The findings above align with general wide-ranging industry trends, where green propellants are recognized for their specific impulse and higher density, enhanced safety, and much lower environmental consequences. Nevertheless, widespread adoption continues to be set back by regulatory, technical, and manufacturing challenges. The complicated integration of this new technology with current, existing propulsion architectures, high development and production costs, and limited flight data/heritage add up to slow regulatory acceptance, especially in the context of adoption in large-scale launch vehicles. Additionally, existing propulsion analysis tools lack needed comprehensive datasets for green propellants, necessitating further computational and experimental validation. The novel framework proposed here emphasizes modular thruster designs, system-level adaptations, periodic flushing protocols, and advanced thermal management to limit observed reliability issues such as catalyst degradation and salt precipitation. Policy implementations include the needs for standardized regulatory incentives and testing protocols to accelerate the transition from hydrazine to green alternatives, especially in recent times of stricter environmental regulations. Practical implications for industrial needs include the improved mission feasibility and potential for reduced operational costs, particularity for use in reusable launch systems and small satellites.

Limitations of the current study include:

- All results are predominantly based on laboratory-scale experiments, computational models, and preliminary demonstration missions, which may not fully represent real-world large-scale space operations.
- Material compatibility and long-term stability of green propellants (particularly HAN and ADN-based) remain uncertain and require extended in-orbit testing. Technical challenges persist with catalyst degradation, ignition system power demands, and salt precipitation in feed systems affecting reliability.
- Limited flight heritage and regulatory acceptance slow broader adoption in primary propulsion applications for large launch vehicles.

- Manufacturing scalability and cost-effectiveness of green propellant formulations and propulsion components have yet to be fully achieved.

- Existing propulsion analysis tools lack comprehensive datasets for green propellants, increasing dependence on further experimental and computational validation.

Looking ahead, future research should prioritize comprehensive in-orbit demonstration campaigns to establish long-term performance and safety data, which are critical for regulatory certification and operational confidence. Innovations in catalyst design, thermal management, and materials science will be pivotal in overcoming ignition and material erosion barriers, enabling more efficient and durable thruster systems. Additionally, development of scalable, cost-effective manufacturing processes and standardized testing protocols will be essential to facilitate industry-wide adoption. Exploring hybrid propulsion architectures and integration of green propellants with emerging mission frameworks, such as small satellites and reusable launch systems, could broaden applicability and enhance mission versatility. Addressing these Chanel; Nges will align propulsion technologies with evolving environmental regulations and sustainability goals, ultimately fostering safer, more eco-friendly space exploration.

V. Conclusion & Future Scope

The integration of green propellants into advanced chemical propulsion systems represents a pivotal advancement toward safer and more sustainable rocketry. This research indicates that green propellants can match or even exceed performance levels compared to those of conventional hydrazine, while also significantly reducing environmental and operational hazards. Yet, the path to widespread adoption of these propellants is constrained by technical challenges, regulatory limitations, and manufacturing complexities. System-level engineering innovations and comprehensive in-orbit validation are required for overcoming these barriers, ensuring reliable and eco-friendly propulsion for future space missions. As global sustainability objectives and regulatory frameworks continue to evolve, the aerospace industry must embrace and prioritize green propellants as a foundational component of responsible future space exploration.

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