SIJRI: Vol.2, Issue 4, April 2026 Page: 62-81 ISSN: 3107-9334

SCRIPTORA
INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION
(SIJRI)
Scriptora International Journal of Research and Innovation (SIJRI)
Journal Homepage: https://scriptora.org

Green Propellants and Smart Energetic Materials for Space Applications

Dr Payal N. Bhautik
Assistant Professor,
Department of Chemical Engineering,
Priyadarshini College of Engineering,
Nagpur, Maharashtra, India
ORCID: 0000-0002-4982-7127

Mrs. Minal Patil
Assistant Professor,
Department of Chemical Engineering,
Priyadarshini College of Engineering,
Nagpur, Maharashtra, India
ORCID: 0009-0004-4450-1576

Abstract

The rapid evolution of space exploration and satellite technology has intensified the need for safer, more sustainable, and highly efficient propulsion and energy systems. This review provides an integrated analysis of the current advancements in green propellant technologies, smart energetic materials, and nanotechnology-driven energy solutions for space applications. This review systematically explores green propulsion methods, including novel monopropellants, hybrid systems, and environmentally benign alternatives. Recent breakthroughs in fuel cell development for spacecraft power and closed-loop life support systems are compared, along with emerging rocket propellant chemistries, such as electrically controlled solids and metal boride nanocomposites. Furthermore, chemical synthesis strategies essential for life support in space habitats are discussed, focusing on oxygen and water recycling. Advances in nanoscale engineering for energy-efficient aerospace materials and defense applications are also discussed. By synthesizing the current literature and providing comparative analyses, this study identifies key opportunities and unresolved research gaps in realizing eco-friendly, high-performance solutions for space missions. The review concludes with recommendations for future interdisciplinary research in chemical engineering and technology, emphasizing the role of green innovation in shaping the next era of sustainable-space exploration.

Keywords: Green propulsion, energetic materials, fuel cells, rocket propellants, chemical synthesis, nanotechnology, life support, space technology

1. Green Propulsion Technologies for Space Missions

Scharlemann (2009) presents a comprehensive assessment of green propellants focusing on their suitability and applicability as alternatives to traditional toxic propellants like hydrazine and nitrogen tetroxide, emphasizing reduced toxicity, operational safety, and environmental benefits. The study outlines a systematic evaluation framework used by the GRASP consortium, considering toxicity, performance metrics such as specific impulse and impulse density, storability, and development status to identify promising green monopropellants, bipropellants, and hybrid fuels. The assessment highlights hydrogen peroxide and nitrous oxide as the most viable storable oxidizer alternatives, with several low-toxicity fuels including ethanol, isopropyl alcohol, kerosene, and turpentine emerging as favorable options. Performance comparisons suggest that many green propellants offer comparable or improved specific impulse density relative to traditional propellants, though some incur slightly lower specific impulses. The study also discusses challenges involving material compatibility, ignition reliability, and long-term storage stability, and stresses that widespread adoption depends on overcoming technical and economic barriers. The GRASP project aims to provide the industry with a reliable database and downselection of green propellant candidates to support safer, more sustainable space propulsion systems for future missions [1].

Shekhawat and Gupta (2018) present a comprehensive survey on green propulsion technologies for spacecraft, addressing the evolution, benefits, challenges, and environmental impacts of various propulsion approaches including electric propulsion, solar sails, and green chemical propellants. The review emphasizes the shifting focus from traditional toxic propellants to sustainable alternatives that reduce space debris and ecological contamination. It highlights the efficiency gains of electric propulsion systems like ion and Hall thrusters, the potential of solar propulsion through solar sails for long-duration missions, and the promise of green chemical propellants such as ammonium dinitramide (ADN) and hydroxylammonium nitrate (HAN) for enhancing environmental safety. Challenges noted include the technical complexity of integrating new systems, limited thrust capability in electric options, power availability issues for solar propulsion, and high development costs. The authors also discuss regulatory, infrastructure, and public perception barriers while outlining application domains across low Earth orbit maneuvering, geostationary orbit station-keeping, and deep space exploration. Future research directions focus on increasing system efficiency, advancing alternative fuels, enhancing solar sail capabilities, integrating artificial intelligence for propulsion control, and establishing standardization to accelerate widespread adoption of green propulsion technologies [2].

Satheesan et al. (2021) provide a detailed overview of green propulsion as an emerging technology in the space industry, focusing on environmentally friendly alternatives to traditional toxic propellants like hydrazine and nitrogen tetroxide. They highlight the safety and environmental benefits of green propellants, such as ammonium dinitramide (ADN), hydroxylammonium nitrate (HAN), nitrous oxide, and hydrogen peroxide, noting their lower toxicity, improved handling, and greater performance metrics like higher density-specific impulse. Challenges in green propulsion systems related to thermal stability, catalyst development, and material compatibility are discussed alongside advances in propulsion hardware, ignition methods, and fuel formulations. The study underscores the significance of predictive modeling, operational cost reduction, and manufacturing innovations in advancing green propulsion technology. The authors also emphasize the potential of green propulsion to enhance mission longevity, reduce environmental impact, and support safer launch and on-orbit operations, fostering sustainable growth in the space sector [3].

Verma et al. (2024) provide an in-depth review of green propellants, focusing on their advancements as safer and environmentally sustainable alternatives to highly toxic traditional propellants like hydrazine and nitrogen tetroxide used in space propulsion. The paper categorizes green propellants into monopropellants and bipropellants, elaborating on energetic ionic liquids such as hydroxylammonium nitrate (HAN) and ammonium dinitramide (ADN)-based propellants, which provide enhanced performance, lower toxicity, and better storability. The review discusses hydrogen peroxide as both a monopropellant and oxidizer in bipropellant systems, and highlights nitrous oxide as a promising green oxidizer candidate. It also addresses challenges like material compatibility, ignition reliability, and thermal stability. Comparisons of propellant toxicity, performance parameters, and environmental impacts emphasize the benefits of green propellant adoption for mission safety and sustainability. Additionally, the study touches on the use of green propellants in various applications, including boosters, reaction control systems, and manned capsules, and stresses the ongoing research for optimizing formulations to balance performance with ecological and operational advantages [4].

Sarritzu and Pasini (2024) provide a comprehensive performance comparison of green propulsion systems for orbital transfer vehicles (OTVs), highlighting the surge in new space economy activities and the resulting demand for safer, more sustainable propellants for in-space applications. The authors critically review the evolution of upper stage propulsion, emphasizing how the limitations and hazardous properties of traditional toxic propellants like hydrazine have driven researchers toward alternatives, such as hydrogen peroxide, nitrous oxide, and advanced monopropellants. Their work systematically analyzes different propulsion architectures—including monopropellant, bipropellant, hybrid, multi-mode, and self-pressurizing systems—by evaluating system-level parameters such as specific impulse, dry and wet mass fractions, hardware and tankage requirements, and operational versatility. The review underlines the advantages of green propellants in minimizing ground operation costs, simplifying system design, reducing toxicity, and enabling flexible mission architecture, while also noting technical challenges such as limited component compatibility, lower propellant densities, and the need for further material and component validation. Ultimately, the study demonstrates that several green propellant alternatives are performance-competitive with conventional technologies and have the potential to enable a new era of modular, service-oriented, and environmentally conscious space missions [5].

Blondel-Canepari et al. (2024) present a holistic framework for evaluating greener in-space propulsion systems, emphasizing the need to balance propulsive performance, cost efficiency, environmental impact, and reliability when selecting propulsion options for orbital transfer vehicles across diverse mission scenarios. The study compares three liquid bipropellant architectures—legacy MON-3MMH, green 98-HTPRP-1, and self-pressurizing N_2O/Ethane—using life cycle analysis, cost modeling, and reliability assessments, and finds that green propellants like 98-HTPRP-1 can match legacy systems in terms of performance and payload ratio for scientific and commercial missions in Low Earth Orbit, while operational familiarity and mature infrastructure keep legacy toxic propellants preferable for more demanding GEO and lunar missions. Overall, the framework demonstrates that integrating environmental and reliability metrics in early design decisions can promote the adoption of sustainable propulsion technologies, providing mission planners with a versatile tool for informed propulsion system selection and supporting the shift toward eco-conscious space exploration and transport [6].

Kurilov et al. (2024) present a detailed characterization of an ignition system for nitromethane-based green monopropellants, evaluating its potential as a cost-effective and safer alternative to traditional hydrazine propulsion in space applications. Through a series of hot-fire tests, they demonstrate that the newly developed glow plug and oxygen-assisted ignition method significantly reduces preheating time and eliminates the need for expensive catalyst materials, while achieving efficient, stable combustion at lower pressures compared to previous ignition approaches. The study compares nitromethane-based formulations (such as NMP-001) with established green propellants like ADN- and HAN-based systems, highlighting comparable specific impulse and combustion efficiency, but noting that further optimization of storage properties and ignition system power requirements is needed for practical satellite integration. Overall, the research supports the continued advancement and adoption of nitromethane-derived monopropellants as viable candidates for next-generation green propulsion, contributing to lower operational costs, simplified systems, and improved safety in future space missions [7].

Choi et al. (2025) investigate the combustion visualization and liquid jet breakup processes in a hydrogen peroxide–kerosene bipropellant thruster, presenting a novel approach to hot-fire analysis that supports the adoption of green propulsion technologies for in-orbit space missions. Their study leverages optically accessible combustion chambers and shadowgraph imaging techniques to observe the trajectory and atomization behavior of a liquid fuel jet injected into a crossflow of hot, oxygen-rich gases generated from the decomposed oxidizer, validating the auto-ignition capabilities and high combustion efficiency of the propellant system without traditional ignition hardware. The authors further demonstrate that hydrogen peroxide as an oxidizer offers significant safety and operational advantages over legacy toxic propellants, while their experimental results and newly proposed empirical correlations for jet trajectory under high-temperature, high-pressure combustion conditions provide valuable guidance for the optimal design of future green bipropellant thrusters. This work not only enhances the understanding of fundamental multiphase flow dynamics in rocket engines but also highlights the role of advanced diagnostics and modeling in boosting the reliability and performance of environmentally friendly propulsion options [8].

Lee et al. (2025) demonstrate a polyethylene nitrous oxide catalytic decomposition hybrid thruster that utilizes a dual-catalyst bed preheated by hydrogen peroxide, addressing the persistent challenge of excessive catalyst preheating time which can lead to component failure in previous systems. Their experimental work establishes a new configuration combining polyethylene as fuel, nitrous oxide as the oxidizer, H_2O_2 as the preheatant, and distinct platinum and ruthenium-based catalysts to achieve effective decomposition and ignition, culminating in stable operation at chamber temperatures above 500 °C and reliable burn durations. The results confirm that the hybrid approach allows for prompt catalyst activation, avoids fuel blockage issues, and achieves characteristic velocity efficiencies above 0.8, indicating efficient combustion and promising performance for green propulsion applications in small spacecraft, with the authors suggesting further improvements through pre-combustion chamber design and scale-up studies [9].

Han et al. (2025) present a thorough theoretical study on the combustion characteristics of ammonium dinitramide (ADN)-based non-toxic aerospace propellants, focusing on the effects of various initial temperature and pressure conditions on combustion products, equilibrium pressure, adiabatic temperature, and ignition delay time. Their research reveals that ADN propellants exhibit a distinct two-stage combustion process under low-temperature and low-pressure conditions, which merges into a single stage at higher temperature and pressure due to accelerated reaction rates. Temperature plays a more significant role than pressure in shortening ignition delay times and increasing combustion rates, with ignition delay decreasing from 3.5 ms to 0.6 ms as temperature rises from 400 K to 2800 K at 10 atm pressure. The study also details the variation of combustion products such as N_2O, N_2, CO_2, and OH during the process and provides insights into optimizing ADN propellant performance for sustainable and high-performance aerospace propulsion [10].

Gut et al. (2025) report on the development and testing of a throttleable 6 kN hydrogen peroxide (98% concentration) and butyl alcohol bipropellant rocket engine aimed at providing a versatile and environmentally friendly propulsion solution for planetary landers and interplanetary missions. The study emphasizes the importance of green propellants following regulatory restrictions on toxic fuels like hydrazine and explores butyl alcohol as a low-toxicity, safe, storable fuel paired with high-test peroxide oxidizer. Engine design incorporates catalytic decomposition of hydrogen peroxide for ignition and employs an advanced pintle injector to achieve stable combustion and precise thrust modulation across a wide throttling range (1.2 kN to 6 kN). Experimental results demonstrate stable performance, efficient combustion, and the critical influence of injector geometry and combustion chamber design on thrust consistency, confirming the system's potential for fine maneuvering tasks in space while addressing operational safety and environmental concerns. This work marks a significant advancement in the integration of throttleable green propulsion systems, supporting future sustainable space exploration missions [11].

Bhosale et al. (2025) investigate the combustion performance and stability of hypergolic ionic liquid fuels composed of 1-ethyl-3-methylimidazolium thiocyanate (EMIMSCN) with copper(I) thiocyanate (CuSCN) additives combined with 95 wt% hydrogen peroxide as an oxidizer in a 50 N thruster. Their study evaluates different injector designs and chamber pressures to understand the effects on ignition delay time, combustion efficiency, and instability. The authors demonstrate that adding 5 wt% CuSCN to EMIMSCN reduces ignition delay from 24 ms to 14 ms, while the density and thermal stability of the fuel improve due to additive interactions. Hot-fire tests reveal that injector pressure drop and fuel injection velocity ratio critically influence combustion stability, with a higher injector pressure drop (40-50% of chamber pressure) achieving significantly reduced instabilities. The fuel formulation achieved combustion efficiencies above 79-83%, with theoretical performance showing competitive specific impulse and characteristic velocity relative to traditional hypergolic fuels. This research highlights the potential of ionic liquid fuels as green hypergolic propellants, promoting enhanced safety, environmental sustainability, and operational reliability for future in-space propulsion systems [12].

Okninski et al. (2025) provide a comprehensive overview of the development and testing of green bipropellant thrusters and engines using 98% hydrogen peroxide (HTP) as an oxidizer, emphasizing nearly 15 years of experience with 98 HTP and over 10 years of bipropellant research. The authors discuss various propulsion system types including quasi-hypergolic, hypergolic, and throttleable engines, highlighting advancements in catalyst technology, combustion chamber materials, injector design, and testing at sea-level and vacuum conditions. Key achievements include the GRACE liquid apogee engine demonstrating stable performance and catalyst longevity, the throttleable TLPD engine enabling deep throttling down to 10% of nominal thrust with high efficiency, and the HIPERGOL hypergolic engine achieving rapid ignition and reliable multi-burn operations. The research underscores the potential of 98 HTP bipropellants to compete with traditional toxic propellants like MON-MMH, offering environmentally friendly, storable, and high-performance propulsion solutions for satellite, launch vehicle, and in-space transportation applications. Furthermore, commercialization efforts and industrialization strategies are discussed alongside challenges in fluidic component development, long-term storability, and system integration needed to advance these green propulsion technologies to flight readiness [13].

Algharrash et al. (2025) present a comprehensive review of green propulsion technologies emphasizing their advancements, applications, and future prospects for sustainable space operations. The paper highlights the urgent industry shift from toxic hydrazine-based propellants toward environmentally friendly alternatives such as high-test hydrogen peroxide (HTP), nitrous oxide-based systems, and ionic liquid fuels. These green propellants offer comparable or superior performance metrics, including specific impulse, density, storability, and handling safety, while significantly reducing toxicity and environmental impact both on Earth and in space. The review covers the integration of these technologies across satellite classes, from CubeSats to large orbital platforms, detailing mission-specific propulsion requirements and practical demonstrations like NASA's Green Propellant Infusion Mission and ESA's PRISMA satellite. Key technical challenges such as thermal stability, catalyst development, ignition reliability, and system compatibility are discussed alongside performance trade-offs and benefits in mass, volume, and operational cost savings. The synthesis underlines how green propulsion systems enable safer ground operations, extended mission lifetimes, and scalable solutions adaptable to diverse mission profiles, positioning them as pivotal for the sustainable growth of the global space economy. Future research directions and a strategic industry roadmap are outlined to address existing limitations and accelerate the adoption of green propulsion in commercial and scientific spaceflight endeavors [14].

2. Fuel Cell Technologies for Space Applications

2.1 Recent Fuel Cell Innovations

Kenneth A. Burke (2003) examined the potential application of fuel cell technology for space science missions, highlighting its advantages over traditional battery systems in terms of energy and power density. In his study presented at the 1st International Energy Conversion Engineering Conference, Burke analyzed Proton Exchange Membrane Fuel Cells (PEMFC) and Direct Methanol Fuel Cells (DMFC) as viable alternatives to conventional primary and secondary batteries used in both manned and unmanned NASA missions. The study revealed that fuel cells could achieve energy densities exceeding 500 W·hr/kg and power densities greater than 500 W/kg, making them suitable for high-power, lightweight energy storage applications such as space probes and planetary rovers. However, Burke noted that the adaptation of fuel cells for space missions would require miniaturization of the fuel cell stack and reduction of ancillary equipment to ensure compact and efficient operation. The research also emphasized that while secondary (regenerative) fuel cells offered potential mass savings, they might not yet compete with batteries on a volumetric basis. The paper concluded that the development of lightweight, high-pressure gas storage systems and passive operational designs would be critical to realizing the advantages of fuel cells in future space science applications **[15]**.

Zhang et. al., (2003) explored the potential of biomass-based fuel cells as sustainable energy systems for manned space exploration, focusing on converting human feces and other biodegradable wastes into usable fuels such as methane and hydrogen. Their study emphasized that utilizing human waste as a resource could significantly reduce fuel transport requirements from Earth while simultaneously addressing waste disposal challenges during long-duration missions, such as those planned for Mars. The researchers investigated both conventional and biological fuel cell systems integrated with anaerobic digestion processes to generate electricity and water from organic waste materials. They concluded that, although current systems exhibit nearly zero net energy output, they remain valuable for their dual benefit of waste treatment and partial energy recycling in space habitats. The report further suggested that using pure oxygen or alternative strong chemical oxidants like potassium permanganate could increase power density and energy yield, making the biological fuel cell more efficient for extraterrestrial applications. Continued research into on-site oxygen production and optimized bioelectrochemical systems was recommended to enhance the feasibility and energy efficiency of biomass-based fuel cells for future manned missions **[16]**.

Krishen (2008) discussed the significance of emerging technologies in advancing human and robotic space exploration, emphasizing their role in achieving safe, reliable, and cost-effective missions. In his paper published in *Acta Astronautica*, he outlined NASA’s vision to extend human presence across the solar system, supported by infrastructural and operational developments derived from experiences with the International Space Station. The study identified several innovative technologies with potential applications in long-duration space missions, including ionic polymer–metal composites, solid-state lasers, nanotechnology, high-temperature superconductors, variable specific impulse magnetoplasma rockets (VASIMR), and advanced computational methods like fuzzy logic, wavelet technology, and neural networks. Krishen highlighted that these technologies could enhance performance, safety, and efficiency while addressing the unique challenges posed by lunar and Martian environments. The paper emphasized that although space conditions impose strict constraints related to mass, power, and cost, continued research and modifications of terrestrial innovations could lead to their practical integration into space systems. The study concluded by stressing the importance of sustained technological advancement to ensure successful future exploration and habitation beyond Earth **[17]**.

Garche and Jörissen (2015) provided a comprehensive assessment of the development, commercialization, and future prospects of fuel cell technology across multiple sectors, including transportation, stationary power generation, and portable applications. Their paper traced the historical evolution of fuel cells from early innovations by Schoenbein, Grove, and Francis T. Bacon to modern advancements driven by environmental policies and rising energy demands. The authors highlighted that significant technological progress has been achieved in Proton Exchange Membrane Fuel Cells (PEFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs), with improvements in power density, durability, and cost reduction. Despite successful demonstrations of hydrogen fuel cell vehicles by major automotive companies such as Toyota, Hyundai, and Honda, widespread market adoption remains constrained by high production costs, infrastructure limitations, and material challenges, particularly the reliance on platinum catalysts. The study also noted promising expansions in stationary applications such as residential combined heat and power systems and industrial installations, especially in Japan, where over 100,000 residential units were operational by 2015. Additionally, the authors described promising market performance in fuel cell-powered forklifts and buses, although commercial viability still depends on government incentives and stricter emission regulations. Garche and Jörissen concluded that while fuel cell technology has reached technical maturity in several fields, achieving cost parity and scaling production remain the primary challenges for full market penetration in the coming decades **[18]**.

Jha (2013) presented a detailed overview of next-generation batteries and fuel cells, emphasizing their applications across commercial, military, and space domains. In his book *Next-Generation Batteries and Fuel Cells for Commercial, Military, and Space Applications*, he discussed the performance characteristics, limitations, and material requirements of various rechargeable batteries such as lead-acid, nickel-cadmium, nickel-metal hydride, and lithium-based systems, focusing on factors like cost, weight, reliability, and charge-discharge efficiency. Jha highlighted how the increased demand for long-duration portable power in military and consumer electronics has accelerated interest in fuel cells as reliable alternatives to lithium batteries. He identified direct methanol fuel cells (DMFCs), zinc-air fuel cells (MFCs), phosphoric acid fuel cells (PAFCs), proton exchange membrane fuel cells (PEMFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) as the most promising types, each with distinctive performance advantages and efficiency levels. The author noted that PEMFCs are gaining traction for distributed power generation due to their design simplicity, low operating costs, and high reliability. He further emphasized that fuel cells’ modularity, fuel flexibility, and environmental compatibility make them suitable for spacecraft, defense systems, and unmanned vehicles, where reliability and operational independence are vital. Jha concluded that continued innovation in materials and design, combined with focused research support, would enable fuel cells to meet future power demands across terrestrial and aerospace applications **[19]**.

Brey et al. (2017) explored the integration of fuel cell and electrolyzer technologies in space applications with a focus on energy storage, propulsion, and deorbitation systems. Their study, presented in *E3S Web of Conferences*, examined two primary aspects of hydrogen usage—gas generation and power production—and evaluated methods such as bioethanol reforming and proton exchange membrane (PEM) electrolysis for hydrogen and oxygen generation in both terrestrial and onboard space systems. The authors analyzed various applications of fuel cells, including their roles in spacecraft landers, auxiliary power units, unmanned aerial vehicles, and stationary backup systems. A significant contribution of this work was the comparison between reversible fuel cell systems, which operate alternately as fuel cells and electrolyzers using a closed-loop water-gas cycle, and regenerative fuel cell systems (RFCS), which employ separate fuel cell and electrolyzer units linked to gas and water storage tanks. The reversible system demonstrated high reliability, compact design, and reduced system mass, making it suitable for small-scale missions like picosatellites. Meanwhile, RFCS configurations showed potential as substitutes for conventional batteries in larger spacecraft due to their higher energy density, mass efficiency, and enhanced power supply consistency. Brey et al. concluded that the continued development and integration of hydrogen-based energy systems could greatly advance sustainable and efficient power management in next-generation space missions **[20]**.

Guo et al. (2017) conducted a comprehensive review on gas, water, and heat management in proton exchange membrane (PEM)-based fuel cell and electrolyzer systems for space applications, emphasizing the need for efficient thermal and fluid control under microgravity conditions. Their study, published in *Microgravity Science and Technology*, traced the historical use of hydrogen-oxygen fuel cells in space missions such as Gemini, Apollo, and the Space Shuttle, and identified PEM-based systems as key technologies for future spacecraft due to their high energy and power density. The authors discussed various active and passive techniques for reactant supply, gas humidification, water removal, and phase separation to enhance performance and durability. Experimental investigations highlighted how microgravity influences two-phase gas-liquid flow, water removal, and overall cell efficiency, showing that water management can perform better in short-term microgravity compared to terrestrial conditions. The paper further outlined passive thermal control strategies, including conductive cooling plates and planar heat pipes, which effectively reduce mass and parasitic power loss while improving reliability. Guo et al. concluded that while passive management technologies have demonstrated strong theoretical and laboratory success, practical validation in actual space environments remains limited, and further microgravity testing is essential to advance PEM-based fuel cells and electrolyzers toward operational readiness for future space exploration missions **[21]**.

Giacoppo et al. (2019) developed and experimentally tested a 2 kW modular proton exchange membrane (PEM) fuel cell stack designed for space applications, particularly for manned lunar exploration missions. Published in *Applied Energy*, the study presented the design, manufacturing, and qualification of a breadboard configuration composed of two 500 W modules capable of operating with pure hydrogen and oxygen under low humidification levels using commercial membrane electrode assemblies (MEAs). The authors evaluated the system’s performance under various conditions, including cyclic loads, orientation changes, and simulated lunar surface operations, to assess its adaptability, reliability, and durability. Results demonstrated excellent stability, high dynamic response to varying power demands, and no significant degradation during long-term and cyclic testing, achieving an efficiency of approximately 55% at nominal power. The stack maintained operational capability even at inclinations up to ±45°, although performance declined at ±90°, indicating sensitivity to gravitational orientation in low-gravity scenarios. The study also revealed that assembly sequence affected voltage distribution and overall performance uniformity between the two stacks. Giacoppo et al. concluded that while the developed PEM fuel cell stack shows strong promise as a regenerative energy source for lunar missions, improvements in the reliability and robustness of commercial MEAs are necessary before practical deployment in actual space environments **[22]**.

Akinyele et al. (2020) presented a comprehensive review of fuel cell technologies and their applications in sustainable microgrid systems, emphasizing their potential as clean, efficient, and reliable energy solutions for distributed generation. Published in *Inventions*, the study detailed the historical development, technological classifications, operational characteristics, and performance comparisons of various fuel cell types, including proton exchange membrane (PEMFC), solid oxide (SOFC), phosphoric acid (PAFC), alkaline (AFC), molten carbonate (MCFC), and direct methanol fuel cells (DMFC). The authors analyzed each technology based on key parameters such as efficiency, power and energy density, temperature range, lifespan, and cost, highlighting that PEMFCs and SOFCs demonstrate superior energy conversion and specific power, making them ideal candidates for future energy systems. The review identified their technical merits—such as modularity, low emissions, and high efficiency—and the challenges associated with high costs, material degradation, and sensitivity to impurities. Additionally, the study explored the integration of fuel cells into microgrids for grid-connected, standalone, and hybrid configurations, showing their capability to enhance grid resilience and provide reliable power in remote or off-grid locations. The authors also discussed the developmental stages of different fuel cell generations, noting that phosphoric acid and molten carbonate fuel cells are commercially ready, while solid oxide and direct methanol fuel cells are progressing toward commercialization. Akinyele et al. concluded that fuel cell technologies hold strong promise for advancing sustainable energy infrastructures, yet further research and policy support are necessary to lower costs, extend lifespans, and improve safety for large-scale microgrid deployment **[23]**.

Qasem and Abdulrahman (2024) presented a comprehensive review of the evolution, fundamental principles, classifications, and modern applications of fuel cell technologies, highlighting their potential to advance sustainable power systems across multiple sectors. Published as *A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications*, the study examined the performance and characteristics of major fuel cell types, including proton exchange membrane (PEMFC), direct methanol (DMFC), solid oxide (SOFC), phosphoric acid (PAFC), alkaline (AFC), and molten carbonate fuel cells (MCFC). The authors compared these technologies in terms of efficiency, operational temperature, energy and power density, lifetime, and cost, concluding that PEMFCs—offering specific power above 1,000 W/kg—are ideal for portable and transportation applications due to their low operating temperatures, rapid startup, and high efficiency. SOFCs and MCFCs, operating at 800–1,000°C, were identified as more suitable for high-power, high-temperature applications, while PAFCs and AFCs provide stability and durability in stationary systems. Although hydrogen fuel cells promise a major role in decarbonizing transportation and aviation

through their lightweight design and zero-emission operation, the study emphasized challenges related to hydrogen production, storage, and system integration under varying environmental conditions. Qasem and Abdulrahman concluded that future research should prioritize cost reduction, material durability, and operational stability to fully realize the potential of fuel cells as key components in the global transition to clean and efficient energy systems **[24]**.
Sharma and Santasalo-Aarnio (2025) present an extensive review of energy storage systems for space applications, emphasizing how batteries, fuel cells, supercapacitors, flywheels, and thermal energy systems must meet unique engineering and environmental demands for transport and outpost missions in space. Their work systematically compares technologies across key metrics such as specific energy, cycle and shelf life, power density, and temperature tolerance, finding that lithium-ion batteries and regenerative fuel cells dominate for short- to long-range missions due to reliability and versatility, while latent heat thermal energy systems and supercapacitors are increasingly adopted for specific applications requiring high impulse or resilience to extreme fluctuations. The authors highlight recent innovations like additively manufactured electrochemical devices, phase-change materials derived from lunar regolith, advanced graphene supercapacitors, and integrated energy-water systems to support sustainable power generation and resource utilization in space habitats. They conclude that optimizing energy storage solutions with in-situ resource utilization, integration with life support and propulsion, and adaptation to harsh conditions is crucial for enabling safe, efficient, and long-term human and robotic presence beyond Earth **[25]**.

2.2 Integration and Performance in Spacecraft

Belz (2016) presented an analytical study on the synergetic use of hydrogen and fuel cells in human spaceflight power systems, emphasizing their integration with life support subsystems for optimized mass efficiency and energy utilization. Published in *Acta Astronautica*, the paper examined how hydrogen, produced through water electrolysis and stored in high-pressure tanks, can be re-electrified by fuel cells while simultaneously supporting life support technologies such as carbon dioxide removal and waste combustion. Using equivalent system mass (ESM) analysis, Belz compared multiple energy storage configurations including lithium-ion batteries, regenerative alkaline fuel cells (R-AFCs), regenerative polymer electrolyte fuel cells (R-PEFCs), and regenerative solid oxide fuel cells (R-SOFCs) across various mission scenarios such as lunar bases, Mars transfer vehicles, and orbiting systems. The results revealed that R-AFC and R-PEFC systems offer lower system mass than R-SOFCs, although R-SOFCs become advantageous under conditions where heat recovery or carbon dioxide electrolysis is needed, such as on the Martian surface. Additionally, the regenerative PEFC system demonstrated stronger integration potential with life support systems (LSS) because it can utilize cabin air for cathode gas supply and share oxygen and water generation cycles, creating a closed-loop and resource-efficient system. Belz concluded that while lithium-ion batteries remain lighter for short-term use, regenerative fuel cell systems provide significant advantages in energy density, mission autonomy, and system synergy, recommending further research to reduce the mass and volume of electrolyzers to enhance competitiveness and overall spacecraft efficiency **[26]**.
Guzik et al. (2017) presented a detailed study on regenerative fuel cell (RFC) power systems for future lunar and Martian surface missions, focusing on the development of a unified architecture for modular and efficient energy storage. In their paper presented at the AIAA SPACE and Astronautics Forum and Exposition, the authors described NASA's Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project, which evaluated multiple RFC configurations to identify viable solutions for sustained surface operations where solar energy availability is intermittent. The study compared regenerative fuel cells with battery-based storage and concluded that RFCs become significantly more advantageous for long-duration energy storage, particularly on the Moon, where eclipse periods can last up to 360 hours. The authors identified Proton Exchange Membrane (PEM) electrolysis as the most suitable technology due to its high technical readiness level, operational flexibility across pressure and flow ranges, and better system integration compared to solid oxide electrolyzers, which remain limited by mechanical seal issues. The team proposed a modular, evolvable development approach allowing incremental advances in fuel cell, electrolyzer, and integrated system components, enabling near-term ground demonstrations that could evolve into flight-ready systems by the mid-2020s. Guzik et al. concluded that a standardized RFC architecture, combining PEM fuel cells and PEM electrolyzers, would provide a cost-effective and scalable solution for NASA's future human and robotic missions, supporting both lunar bases and Martian habitats with high energy density, reliability, and potential integration with life support and in-situ resource utilization systems **[27]**.
Hexu Sun et. al., (2023) provided an insightful review on the synergetic utilization of hydrogen and regenerative fuel cells (RFCs) in human spaceflight power systems, highlighting their integration with life support and propulsion subsystems to optimize mass efficiency and resource utilization. Presented in *Acta Astronautica*, the study focused on surface power systems for lunar and Martian exploration missions, emphasizing the critical need for reliable energy storage to complement intermittent solar power availability during extended nocturnal periods. Using equivalent system mass (ESM) analyses, Belz compared alkaline and polymer electrolyte membrane RFC designs, finding that Regenerative PEM Fuel Cell (R-PEFC) systems tend to offer better integration with life support systems by enabling

oxygen supply through cabin air, while alkaline systems face challenges related to purity and carbon dioxide sensitivity. The paper underscores the advantages of a modular, unified RFC architecture utilizing PEM electrolyzers and fuel cells as the most promising near-term approach for diverse mission scenarios. This architecture not only delivers efficient energy storage and power generation but also allows reuse of water and oxygen within closed-loop cycles, significantly enhancing mission sustainability and reducing overall system mass. Belz recommended advancing technology development by 2025 to meet NASA's mid-2030s mission timeline, focusing on the reduction of mass and volume of system components, improving electrolysis efficiency, and validating integration strategies with other surface systems **[28]**.

Feng et al. (2024) reviewed the integrated energy system of fuel cells for space applications, emphasizing comprehensive utilization of water, gas, and thermal energy in spacecraft environments. Published in the *Journal of Physics: Conference Series*, their study highlighted how fuel cells use hydrogen and oxygen from liquid propellant tanks for power generation, while recovering waste heat through dual-channel heat exchangers to preheat incoming gases, and reusing produced water via static drainage systems for thermal and environmental control. A prototype fuel cell system delivering stable 400 W power showed fuel utilization efficiency exceeding 97% and water recovery efficiency over 95%, illustrating a highly efficient closed-loop design. The authors discussed the essential roles of gas, thermal, and water management units in maintaining stable operating conditions by controlling gas pressures and temperatures, dissipating heat passively with cold plates, and managing water via circulation pumps and self-humidification methods adapted for microgravity. They further detailed an integrated fuel cell stack architecture optimizing fluid, thermal, and electrical management, achieving compact, lightweight system design suited for the rigorous demands of space missions. Feng et al. concluded that regenerative fuel cell systems provide unique advantages by synergistically integrating power generation with spacecraft propulsion, thermal control, and life support, thus offering a sustainable and high-efficiency energy solution for future manned space exploration, albeit with ongoing challenges in demonstration and verification for space deployment **[29]**.

3. Advanced Rocket Propellants and Combustion Systems

Forbes and Van Splinter's (2019) work on liquid rocket propellants offers a thorough exploration of the essential characteristics, performance metrics, and handling considerations crucial for selecting and utilizing propellants in rocket propulsion systems. Their analysis highlights the importance of maximizing chemical energy release through optimized combustion processes that produce hot gases with low molecular weight to achieve high specific impulse and efficient thrust. The authors emphasize the physical and chemical stability requirements of propellants, such as storability over extended periods without decomposition, low freezing and boiling points suitable for operational environments, and safe handling protocols to manage toxicity, reactivity, and material compatibility issues. They discuss various propellant types, including bipropellants (separate fuel and oxidizer), monopropellants, and tripropellant mixtures, noting trade-offs among performance, ease of storage, safety, and cost. The book addresses challenges associated with cryogenic fuels like liquid hydrogen and oxygen, whose high performance is offset by difficulties in storage and handling due to low temperatures and high vapor pressures. Additionally, it covers storable propellants with longer shelf lives but lower performance metrics. Detailed attention is given to material selection for storage and feed systems to avoid corrosion and ignition hazards, and to procedures ensuring operational safety. Overall, the book integrates theoretical fundamentals with practical engineering insights, making it an indispensable resource for understanding and optimizing liquid rocket propellant performance in aerospace propulsion [30].

Sutton and Biblarz's "Rocket Propulsion Elements," Seventh Edition, is widely regarded as the authoritative text on rocket propulsion technology, extensively covering classification, theory, design, and practical aspects of liquid, solid, hybrid, and electric propulsion systems [30]. The book comprehensively addresses fundamental propulsion concepts, nozzle theory, thermodynamics, and engine performance metrics critical for aerospace engineering. With detailed explanations supported by over 340 illustrations, tables, and problem-solving examples, it serves both as a foundational learning resource for students and a practical reference for professional engineers in aerospace and defense industries. The latest edition incorporates advances in launch vehicle propulsion, spacecraft systems, and emerging technologies such as aerospike nozzles and electrical propulsion, reflecting contemporary developments in the field. Sutton and Biblarz focus on integrating theoretical rigor with real-world design considerations, making the text essential for understanding and developing rocket propulsion elements across diverse aerospace applications [30],[31].

3.1 Electrically Controlled Solid Propellants

Glascock et al. (2023) investigated the performance of electric solid propellants (ESPs) in ablative pulsed plasma thrusters, comparing them against the industry-standard polytetrafluoroethylene (PTFE) propellant using a micro-Newton thrust stand. Their study highlighted that ESPs, which ignite and combust controlled by electric current, offer advantages over traditional solid propellants due to their throttleability, safety, and on-demand ignition capability.

Experimental results demonstrated that ESPs exhibit higher ablation mass loss per pulse than PTFE, although specific impulse values are somewhat lower, primarily due to absorbed water evaporation effects in ESPs. The research provided detailed impulse-per-pulse and specific impulse measurements across varying energy levels, offering critical insights into the thrust efficiency and performance characteristics of these advanced propellants for space propulsion. While ESPs show promise for multimode electric propulsion applications, current limitations including ablation efficiency and atmospheric moisture sensitivity suggest the need for further development before deployment in operational space thrusters. This work significantly advances understanding of ESP behavior in pulsed electric thruster environments, supporting next-generation solid propellant designs with enhanced controllability for space missions [30].

Zhang et al. (2024) conducted an in-depth study on the design, fabrication, and performance characterization of electrically controlled solid microthrusters (ECSP) tailored for micro/nano satellite applications. Their research focused on optimizing the propellant composition—specifically varying aluminum (Al) content—to enhance ignition delay, energy requirements, mass loss, extinction delay, and thrust outputs. The study demonstrated that higher Al content (around 10%) significantly improves combustion stability, reduces ignition delay and energy, and increases thrust, while lower Al concentrations caused unreliable ignition and poor combustion performance. The microthruster was fabricated using vacuum mixing techniques to minimize bubbles, with detailed morphological assessments via SEM and micro-CT confirming dense, uniform propellant structures. Experimental tests using variable loading voltages elucidated that combustion characteristics and thrust generation are voltage-dependent, with optimal performance at higher voltages coinciding with rapid ignition and increased mass loss. These findings underscore the potential of ECSP technology as a safe, controllable, and adjustable propulsion option for precise attitude control and orbit transfers in small satellite missions, contributing significantly to the advancement of solid propulsion microthruster designs with electrical ignition and throttling capabilities [31].

Wang et al. (2024) provided a comprehensive review of electrically controlled solid chemical propulsion (ECSP), highlighting it as a transformative technology for intelligent solid propulsion systems with on-demand ignition, extinguishment, and programmable thrust output capabilities. Their study, published in the *Chemical Engineering Journal*, traced ECSP development milestones including propellant formulation design, combustion diagnosis, and mechanistic understanding. ECSP technology overcomes the longstanding rigidity of traditional solid rocket motors by enabling active combustion control through electrical energy input, allowing precise thrust modulation without reliance on mechanical adjustments. The review emphasized advancements in coupling electrical energy with chemical reactions for spontaneous burning rate control, as well as innovations in power electronics that support compact, efficient power supply units necessary for ECSP operation. Important applications discussed include satellite attitude control and micro/nano thrusters, demonstrating high insensitivity to accidental ignition and improved operational safety. Despite these advances, the authors identified key technical challenges such as increasing the critical controllable pressure, ensuring scalable electrode designs without sacrificing combustion efficiency, and integrating ECSPs with intelligent ignition systems. The review concluded by underscoring the vast potential of ECSPs to revolutionize solid propulsion and encouraged continued research to resolve remaining engineering hurdles for wider application in aerospace and defense propulsion technologies [32].

Y. Li et al. (2024) delivered a comprehensive review of electrically controlled solid chemical propulsion (ECSP), positioning it as a game-changing technology for intelligent solid propulsion systems with capabilities for on-demand ignition, extinguishment, and variable thrust modulation via electrical inputs. Their work, published in the *Chemical Engineering Journal*, systematically addresses the advancements in propellant formulation highlighting the use of novel ionic liquid oxidizers, flame-retardant polymer electrolytes, and conductive additives that influence key performance factors such as energy density, conductivity, and combustion behavior. The review articulates how ECSPs overcome the traditional limitations of solid rocket motors by enabling active thrust control without mechanical complexity, which is crucial for adaptable and responsive propulsion. Further, the authors discuss various electrode configuration strategies aimed at improving ignition reliability, minimizing erosion, and sustaining electrical contact during combustion. Despite these advances, challenges remain in lowering ignition voltage, expanding controllable pressure ranges, balancing combustion efficiency with energy density, and refining combustion models. Wang et al. underscore the essential role of further research into combustion mechanisms, formulation optimization, and advanced electrode designs to propel ECSP technology toward broader aerospace applications, ultimately fostering safer, smarter, and more flexible solid propulsion systems [33].

3.2 Metal Boride and Nanocomposite Propellants

Pontes Lima et al. (2015) presented a detailed investigation into the synthesis of metal-polymer nanocomposites for fuel applications, emphasizing the significant advantages of incorporating nanosized metal particles, such as aluminum and boron, into propellant formulations to boost energy density and combustion performance. Their research highlighted that reducing particle size to the nanoscale enhances reactivity, leading to faster burning rates and shorter ignition delays, which is crucial for volume-limited rocket propulsion systems where high density-based specific impulse is desired. The study further addressed challenges faced by metals like boron, whose combustion efficiency is hindered by the formation of a stable oxide layer causing prolonged ignition delays, and proposed that additives like aluminum and magnesium can improve combustion by facilitating oxide removal and providing additional heat. Innovative surface treatment methods, including coating metal nanoparticles with energetic polymers such as glycidyl azide polymer (GAP), were explored to prevent premature oxidation and enhance dispersion within polymer binders, resulting in composite materials with improved energetic output and processability. The research also delineated various synthesis methodologies, particularly reactive milling approaches, to create energetically capped metal particles while mitigating issues like by-products and self-polymerization during production. Overall, Pontes Lima et al. demonstrated that metal-polymer nanocomposites represent a promising avenue for next-generation solid propellants, offering enhanced combustion properties and energy density critical for advanced rocket propulsion, although further optimization of particle coatings and processing techniques is required to fully realize their potential [34].

Manning et al. (2016) investigated the innovative use of boron nitride (BN) as an additive in propellants to address the U.S. military’s need for more powerful yet less erosive gun propellants. Their research demonstrated that BN nanoparticles, synthesized via a scalable and economical process, could be evenly dispersed into nitrocellulose-based double-base propellants without destabilizing the formulation. BN acts as a solid lubricant with excellent wear resistance, contributing to significantly reduced gun barrel erosion, longer barrel life, and smoother, less cracked barrel surfaces after firing tests. The hardened steel observations suggest that boron from BN doping may enhance the mechanical strength of gun barrels, potentially blocking softer carbide formation and improving resistance to thermal and mechanical wear. These effects could translate into practical benefits for various caliber firearms, including reduced maintenance costs and enhanced performance consistency. Though initial results are promising, the authors recommended further extended firing tests and quantitative characterization to fully verify BN’s hardening and erosion mitigation mechanisms, underscoring its potential as a strategic additive for advanced military propellants[34] [35].

Grosjean (2018) provided a comprehensive review of boron-based nanomaterials under extreme conditions, highlighting their unique structural, mechanical, and chemical properties that make them highly suitable for advanced fuel applications [36]. The thesis explored various elemental forms and allotropes of boron, emphasizing their stability and performance under high-pressure and high-temperature (HPHT) environments [37]. Special attention was given to boron-metal alloys and nanostructures synthesized via molten salt colloidal methods, which exhibit enhanced thermal stability, mechanical strength, and combustion characteristics. Boron nanomaterials like boron nanowires and nanostructured borides demonstrate exceptional fracture strength, elastic modulus, and oxidation resistance, making them promising candidates for incorporation into high-energy composite fuels [38]. Moreover, the functionalization of boron nanoparticles with energetic polymers such as glycidyl azide polymer (GAP) was highlighted as a strategy to improve dispersion and enhance energetic performance while protecting particles from premature oxidation [39]. Grosjean's work provides critical insights into the synthesis, characterization, and potential of boron-based nanocomposites, paving the way for their optimized use in rocket propellants and other energetic materials under harsh operational conditions.

Nehate et al. (2020) reviewed boron carbon nitride (BCN) thin films and nanomaterials, emphasizing their tunable electrical properties, exceptional mechanical robustness, chemical inertness, and high thermal stability, which render them highly suitable for harsh environment applications. The review discussed various deposition techniques such as chemical vapor deposition, sputtering, and pulsed laser deposition, which influence the structural phases and properties of BCN materials, enabling bandgap engineering from semiconducting to insulating states. BCN nanomaterials exhibit versatile morphologies, including nanoparticles, nanosheets, and nanotubes, with applications spanning electronics, supercapacitors, sensors, catalysis, and environmental remediation. Their unique combination of electrical conductivity, chemical stability, and mechanical hardness enables use in advanced coatings, electronic devices, and energy storage systems. The review highlighted ongoing challenges in thermal conductivity measurements, magnetic property understanding, and scalable synthesis methods, outlining future research directions like heterostructure development and integration with silicon technologies for commercial applications. Overall, Nehate et al. presented BCN nanomaterials as promising multifunctional materials with significant potential across energy, electronics, and environmental fields [38].

Gok and Cihan (2020) reviewed the role of energetic materials and metal borides in solid propellant rocket engines, emphasizing that metal borides such as aluminum boride (AlB2) and magnesium boride (MgB2) are promising as alternative fuels due to their high energy density and superior combustion properties compared to traditional metals. They discussed the synthesis methods for these borides, including mechanical activation and self-propagating high-temperature synthesis (SHS), which are key to producing borides with high purity and quantity. The study highlighted the need for developing new methods to synthesize large amounts of high-purity metal borides to enhance their practical application in rocket propulsion. Gok and Cihan concluded that metal borides, particularly AlB2 and MgB2, hold great potential for advancing the performance of solid rocket engines, meeting the growing demands of military and aerospace propulsion systems [40].

Pang et al. (2021) reviewed the effect of metal nanopowders on the performance of solid rocket propellants, analyzing the combustion behavior and hazardous properties of various nano-sized metal particles including aluminum (nAl), zirconium (nZr), titanium (nTi), and nickel (nNi). Their study emphasized that incorporating nano-sized additives significantly increases the burning rate of propellants compared to micro-sized particles, with nAl promoting direct particle combustion that reduces ignition delay and diffusion length. Despite performance enhancements, they noted that nanoparticles increase impact and friction sensitivity, raising safety considerations. The review also highlighted the formation of core–shell structures on nanoparticles and the improvement of burning rates through surface coatings. While metal nanopowders show promise in enhancing propulsion efficiency, the authors concluded that current applications are largely at the laboratory stage, necessitating further research and development to enable industrial-scale adoption in solid rocket motors [41].

Tay et al. (2023) comprehensively reviewed advanced nano architectures of hexagonal boron nitride (h-BN), focusing on their synthesis, distinctive properties, and emerging applications across diverse fields. They highlighted that h-BN exhibits exceptional thermal stability, mechanical stiffness, chemical inertness, and high thermal conductivity while being electrically insulating, making it suitable for extreme environments and a variety of cutting-edge technological uses. The review detailed various fabrication methods for synthesizing h-BN nanostructures, including 0 D quantum dots, 1D nanotubes and nanoribbons, 2D nanosheets, and 3D porous frameworks, with chemical vapor deposition (CVD) being a versatile but high-temperature method, alongside exfoliation, hydrothermal, solvothermal, and freeze-casting techniques. Tay et al. discussed the tailored properties of these nanomaterials that enable applications in electronics, thermal management, deep ultraviolet optoelectronics, quantum emitters, protective coatings, space instrumentation, and biomedicine, such as drug delivery and biosensing. Despite significant progress, challenges remain in scalability, defect control, contamination-free transfer, and integration with other materials for commercial deployment. The authors underscored the need for continued innovation to overcome these limitations and fully realize the promise of h-BN nanotechnology in industrial and emerging application domains [39].

3.3 Combustion Modeling and Efficiency

Singh et al. (2009) discussed the development and impact of the KIVA computational fluid dynamics (CFD) modeling code under the U.S. Department of Energy's Freedom CAR and Vehicle Technologies Program. KIVA is a sophisticated 3D multiphase flow simulator designed to capture in-cylinder combustion processes in internal combustion engines with high fidelity. The ability of KIVA to model complex phenomena such as liquid fuel spray, vaporization, and combustion acceleration enables engineers to optimize fuel efficiency and emissions while reducing costly experimental iterations. With advancements like KIVA-4 introducing unstructured grid capabilities and multi-species fuel vaporization modeling, KIVA has become an industry-standard tool employed by automotive manufacturers (e.g., General Motors, Cummins) and national labs to enhance engine design. The integration of KIVA in engine R&D has led to significant improvements in engine thermal efficiency (up to 10%) and development cycle time reduction (up to 60%), facilitating the creation of cleaner and more energy-efficient vehicles. This computational approach continues to play a central role in meeting stringent emissions regulations and advancing combustion technology [42].

Cala et al. (2015) evaluated various combustion models to determine refinery furnace efficiency, focusing on the assessment of heat released and absorbed during combustion. Their study compared different models of varying complexity, with Model IV incorporating stack gas temperature, excess air, and furnace wall heat losses providing the most practical and accurate evaluation using just two key variables. Using computer simulations in Aspen HYSYS, the effects of varying fuel gas compositions with lower heating values between 800 to 2500 Btu/ft^3 were analyzed and compared to natural gas data. Results indicated that combustion characteristics, including efficiency and adiabatic flame temperature, are sensitive to fuel composition, with higher hydrogen concentrations reducing efficiency while increasing flame temperature. Their findings support that lower stack gas temperatures correlate with higher combustion efficiency and that increased excess air lowers stack temperature. This research effectively demonstrated that combustion efficiency models based on stack gas temperature and excess air can reliably assess refinery furnace performance, aiding process optimization and energy management in industrial settings [43].

Azad et al. (2015) critically reviewed the recent evolution in biodiesel combustion strategies and modeling for compression ignition (CI) engines, emphasizing the distinctive behavior of biodiesel blends compared to conventional diesel due to differences in physico-chemical properties. They highlighted the effectiveness of low temperature combustion (LTC) strategies—namely homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactive controlled compression ignition (RCCI)—in reducing toxic emissions such as NOx and particulate matter when using biodiesel. However, LTC strategies typically lead to increased brake specific fuel consumption, lower brake thermal efficiency, and higher CO and unburned hydrocarbon (UHC) emissions, primarily because of higher rates of exhaust gas recirculation (EGR). The authors identified the need for advanced predictive combustion models, recommending the shear-stress transport (SST) k-ω turbulence model as an efficient tool for simulating biodiesel combustion under LTC conditions given the highly turbulent, density-variable nature of in-cylinder flows. Their review also pointed out remaining research gaps, including the optimization of mixing charge, EGR ratio, and detailed studies on biodiesel autoignition chemistry, calling for integrative modeling approaches to further improve engine efficiency and control emissions in CI engines running on biodiesel blends [44].

Zhou et al. (2017) proposed an efficient hybrid combustion modeling approach for Reactivity Controlled Compression Ignition (RCCI) engines that integrates detailed chemical kinetics while significantly reducing computational cost. Their model combines characteristic time-scale (CTC) methods for high-temperature species equilibrium with CHEMKIN solvers for low- to intermediate-temperature combustion, embedding this hybrid scheme within the KIVA-4 CFD platform. Validation against experimental RCCI engine data showed close agreement in in-cylinder pressure and heat release rate predictions, demonstrating robust and accurate combustion characteristic simulations. Importantly, the hybrid model achieved approximately 20% computational time savings compared to the sole CHEMKIN approach, making it practical for rapid combustion control design and testing in RCCI engines known for superior thermal efficiency and near-zero emissions. This advancement supports the optimization of RCCI combustion under diverse fuel reactivity and operating conditions, fostering the development of cleaner, more efficient internal combustion technologies [45].

Pelosin et al. (2022) introduced an innovative Low Temperature Combustion (LTC) strategy termed Temperature Controlled Reactivity Compression Ignition (TCRCI) and developed a numerical optimization framework combining Computational Fluid Dynamics (CFD) simulations with Particle Swarm Optimization (PSO) for this advanced combustion system fueled by iso-octane. Their study aimed to mitigate the complexity of traditional RCCI engines by replacing direct injection of high reactivity fuel with heated injection of low reactivity fuel, focusing on enhancing net indicated efficiency (NIE) while decreasing pollutant emissions, particularly CO. The CFD model was rigorously validated against experimental data and optimized parameters included piston bowl geometry, injection timing, and boosting pressure. The optimized configuration featured a wider piston bowl, larger injection angle, delayed start of injection (SOI), and lowered exhaust gas recirculation (EGR), resulting in a 3% increase in NIE and a substantial reduction of CO emissions from 0.407 to 0.136 mg. Pelosin et al. demonstrated that this integrated modeling and optimization approach can effectively guide hardware and operating parameter design to improve combustion efficiency and reduce emissions in TCRCI engines, offering promising directions for future LTC technologies [46].

Glotov et al. (2023) conducted an experimental study on the combustion features of boron-based composite solid propellants, focusing on characteristics of condensed combustion products (CCPs) formed during burning. Using propellants with metallic fuels like aluminum, boron, aluminum diboride, and aluminum dodecaboride under varying pressures, they analyzed burning rates, particle sizes, morphologies, and combustion completeness. The study found distinct morphological differences in CCPs with aluminum forming strong spherical agglomerates and boron producing fragile coral-shaped aggregates, while boron-containing borides showed intermediate features. Despite variations in particle size and pressure, no significant increase in combustion completeness of boron was observed with aluminum additives. The researchers introduced a heat release efficiency parameter to quantify energy output influencing propellant burning rates. Their findings provide valuable experimental data for developing and validating theoretical combustion models for metalized propellants. However, the work acknowledges the need for further studies on different formulations and binders to explore synergistic combustion effects in boron-based propellants [47].

4. Chemical Synthesis for Life Support Systems

4.1 Air and Water Recycling Technologies

4.2 Challenges in Closed-Loop Systems

Drake et al. (1966) conducted a comprehensive study on life-support systems designed for space missions exceeding one year in duration, focusing on creating closed ecological systems capable of recycling human and cabin waste into vital resources such as oxygen, food, and potable water. Their work emphasized the integration compatibility of various life-support subsystems, giving special attention to the relatively less advanced closure of the food-waste loop. The study systematically reviewed biological and physico-chemical subsystems for food synthesis and waste processing, including biosystems based on algae, bacteria, higher plants, and chemical synthesis methods for carbohydrate and protein derivatives. Using a spacecraft system model based on manned planetary mission scenarios, such as Earth-Mars round trips lasting over 500 days, the authors evaluated subsystem configurations to estimate engineering parameters and determined preferred system designs for subsequent research and development phases. This foundational research established technical justifications and planning directions for advancing life-support technologies necessary to sustain long-term human presence in space through fully or partially closed-loop ecological systems [50].

De Luca et al. (2017) edited a comprehensive survey on energetic materials for chemical rocket propulsion, published in the Springer Aerospace Technology series. This work encompasses the entire lifecycle of energetic materials from their conceptual formulation through practical manufacturing, integrating theoretical models and experimental studies related to performance parameters, handling, hazards, environmental effects, aging, and disposal. The survey delves into various classes of propellants including solid, liquid, and hybrid systems and discusses their properties, combustion mechanisms, and contributions to thrust generation and efficiency. It also highlights technological advances in propellant formulations, manufacturing processes, and safety protocols that underpin modern rocket propulsion development. This authoritative collection serves as a critical resource for aerospace engineers, researchers, and designers focused on energetic material innovations and enables deeper understanding of propulsion system optimization for space access and exploration [51]. NASA's 2019 "Breakthrough Materials for Space Applications" Workshop underscored the pioneering role NASA has played over six decades in advancing aerospace materials and transitioning these innovations to industrial applications. The workshop convened over 200 experts from government, academia, and industry across six focus areas: metals, nonmetals, computational modeling, testing and characterization, emerging materials (including low technology readiness materials and novel applications such as nuclear propulsion and in situ resource utilization), and microgravity research on the International Space Station. Speakers emphasized critical needs for new materials to meet the demands of upcoming missions, including lunar exploration and long-duration planetary habitats, which require materials that can endure extreme environments such as microgravity, radiation, vacuum, and high thermal loads while minimizing launch mass and ensuring compatibility and manufacturability. Advances in additive manufacturing, digital design integration, and materials informatics were highlighted as transformative technologies enabling rapid fabrication and complex component design tailored for space conditions. The workshop facilitated knowledge sharing on state-of-the-art materials research and development strategies essential to enable NASA's exploration goals, from habitation modules to propulsion and thermal protection systems, underscoring the ongoing collaborations aimed at overcoming historic materials challenges for deep space missions [52].

García Martínez et al. (2021) explored the chemical synthesis of food from CO2 for long-duration space missions, comparing various space food production systems including non-biological synthesis (NBS) using recycled CO2, prepackaged food, artificial-light grown Spirulina, hydrogen-oxidizing bacteria (HOB), and microbial electrosynthesis (MES). Their study utilized the equivalent system mass (ESM) metric to evaluate launch costs factoring in equipment mass, volume, power, and heat rejection across missions to the ISS, Moon, and Mars. Results indicated that NBS systems offer competitive energy efficiency (10–21% electricity-to-food conversion) and single-pass carbon yields (~70%), with Mars mission ESM estimated between 10-30 tons, outperforming prepackaged food and Spirulina benchmarks. While HOB showed superior ESM and nutritional quality, and MES performed similarly to NBS, the research highlighted NBS as a viable closed-loop food production method, potentially enhancing sustainability and resilience in space habitats and extreme terrestrial scenarios. The authors suggested that integrating these technologies could improve diet diversity and reduce space mission launch mass costs, contributing to existential risk mitigation through food security innovations [53].

Heinicke et al. (2021) provided a comprehensive review of existing analog habitats designed to simulate human life on the Moon and Mars, synthesizing lessons learned from over two dozen active and inactive facilities worldwide and research bases in extreme Earth environments such as Antarctica. Their study reviewed architectural concepts, implemented technologies, and scientific research conducted in these habitats, noting the diversity in accessibility, crew selection, and research focus areas, including human factors, technology development, and environmental studies. Heinicke et al. emphasized that while no current analog habitat is fully suitable for actual planetary missions without major modifications, these facilities still offer critical insights into effective design elements and operational challenges for extraterrestrial habitations. Their recommendations aim to guide researchers in selecting appropriate analogs for mission-specific studies and to inform the design and construction of future habitat prototypes that balance functionality, safety, and crew wellbeing for sustained lunar and Martian exploration [54].

Nosseir et al. (2021) provided a detailed review of state-of-the-art green monopropellants, highlighting their increasing adoption for spacecraft propulsion driven by environmental sustainability and safety concerns. Their study classified green monopropellants broadly into Energetic Ionic Liquids (EILs), Liquid NOx monopropellants, and Hydrogen Peroxide Aqueous Solutions (HPAS), offering comprehensive data on physicochemical properties and performance metrics. These monopropellants, particularly EILs such as AF-M315E and LMP-103S, are favored for small satellite propulsion due to their relatively high performance, storability, and simpler system architecture compared to traditional bipropellants and gaseous fuels. The review underlined the suitability of NOx fuel blends for self-pressurizing systems that simplify feed and pressurization designs, and noted the operational safety and reliability legacy of HPAS propellants like high-test peroxide (HTP). Emphasis was given to challenges in miniaturized propulsion systems for high-thrust impulsive maneuvers typical in small satellites and CubeSats.

Nosseir et al.'s work supports design decisions for next-generation green propulsion technologies, illustrating performance trade-offs and encouraging their expanded utilization in emerging space missions [55].

García Martínez et al. (2021) reviewed the chemical synthesis of food from CO2 as a sustainable food production method for long-duration space missions. Their study compared non-biological synthesis (NBS) systems utilizing recycled CO2 with traditional space food options such as prepackaged meals, artificial-light grown Spirulina, hydrogen-oxidizing bacteria (HOB), and microbial electrosynthesis (MES). Using equivalent system mass (ESM) analysis, they evaluated launch mass costs and operational demands for missions to the ISS, Moon, and Mars. Results suggested that NBS offers superior energy efficiency with electricity-to-food conversion rates between 10% and 21% and carbon yields up to 70%, making it more mass-efficient than prepackaged food or Spirulina systems. Although HOB outperformed NBS in terms of nutritional value and ESM, and MES had similar performance, NBS was favored for its potential in closed-loop life support by synthesizing carbohydrates like sugars and glycerol from CO2. The authors underscored that integrating these technologies could improve diet diversity and sustainability in space and potentially benefit Earth-based food security during global catastrophes, thus contributing to resilient food systems beyond terrestrial limits [56].

Uekert et al. (2023) conducted a comprehensive technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics, including mechanical recycling, solvent-based dissolution, enzymatic hydrolysis, glycolysis, and vapor methanolysis applied to polymers like polyethylene, PET, and polypropylene. Their analysis examined critical metrics such as material quality and retention, circularity, contamination tolerance, minimum selling price, greenhouse gas emissions, energy usage, land and water use, toxicity, and waste generation. Mechanical recycling and PET glycolysis were found to outperform other methods economically (9%–73% lower costs) and environmentally (7%–88% lower impacts), though chemical recycling techniques tended to yield higher-quality recyclates (2%–27% improvement). The study identified electricity, steam, and organic solvents as major contributors to environmental footprints and emphasized the need for advancing process yields, reducing consumables, and decarbonizing utilities. The authors provided a robust methodology for assessing and improving recycling processes and offered a quantitative baseline to guide recyclers toward optimal plastic waste management, supporting efforts for a sustainable circular economy [57].

Karkou et al. (2024) investigated process innovations and circular strategies for closing the water loop in a chemical process industry, focusing on a case study of the Solvay chemical plant. Their research implemented advanced wastewater treatment technologies coupled with digital tools to produce high-quality water for industrial reuse, enhancing process efficiency and promoting circularity. The study evaluated four wastewater treatment scenarios using process simulation modeling (PSM) and life cycle assessment (LCA) to compare environmental impacts. The best-performing scenario involved conventional and advanced treatment combined with industrial water reuse facilitated by a cross-sectorial symbiotic network exchanging effluents among industry, municipality, and water utilities. This approach resulted in a 21% to 36% reduction in environmental footprint compared to scenarios with discharge to sea, significantly reducing pollutant loads like COD, TOC, and nitrates. The authors highlighted the importance of integrating process, circular, and digital innovations alongside collaborative policy frameworks to optimize water reuse, waste reduction, and sustainability in industrial water management, setting the path for broader adoption of circular economy principles in the chemical sector [58].

Ma et al. (2024) reviewed sustainable wastewater treatment and reuse strategies critical for long-term space missions, emphasizing the challenges posed by closed and limited water environments in spacecraft and space habitats. The study traced the evolution of water treatment technologies used in space stations over the past six decades, highlighting the importance of source separation, such as urine separation due to its high nitrogen and salt content, and advanced methods like membrane distillation for high-salinity wastewaters. Ma et al. discussed the need to adapt terrestrial wastewater treatment methods to microgravity and limited convection conditions in space, focusing on enhancing mass transfer efficiency and optimizing water and nutrient recycling. The review further addressed challenges such as energy consumption reduction, microbial behavior under radiation and microgravity, and achieving high closure rates in water recycling systems. Proposing a shift towards high-closure water cycles and integrated wastewater management, the authors underscored the necessity of developing space-specific water treatment theories and technologies to support future deep-space missions and space bases [59].

Harasymchuk et al. (2024) presented a comprehensive overview of chemical recycling methods and technologies addressing the critical global challenge of plastic pollution. Their review detailed an array of chemical processing techniques including hydrolysis, glycolysis, enzymatic degradation, acid hydrolysis, supercritical fluid depolymerization, catalytic and fast pyrolysis, microwave pyrolysis, fluidized bed pyrolysis, plasma gasification, steam gasification, oxidative degradation, hydrothermal liquefaction, biological depolymerization, and electrochemical processing. The authors highlighted the technological readiness levels (TRLs) of these methods, ranging from laboratory scale to commercial deployment, emphasizing the environmental and economic impacts associated with each. Key challenges identified include high energy consumption, process emissions, need for renewable energy integration, and scalability. The review underscored the necessity for coordinated advancements in catalyst development, process optimization, policy frameworks, and industry collaborations to overcome current limitations and support large-scale, sustainable chemical recycling as an indispensable component of a circular economy for plastics [60].

Yalin et al. (2025) presented a pioneering study on a light-driven closed-loop chemical recycling system for polypinacols, addressing the urgent need for sustainable polymer recycling solutions amid the escalating plastic waste crisis. Their research demonstrated the use of photochemical excited-state chemistry, employing an earth-abundant cerium photocatalyst to selectively cleave stable C─C bonds of hydroxyl-rich polymers under visible light at ambient conditions, effectively regenerating the original monomers. This light-driven approach contrasts with traditional thermal methods by operating at lower temperatures with higher energy efficiency and reduced side-product formation. Yalin et al. successfully polymerized bis-aldehyde monomers into well-defined polypinacols exhibiting excellent thermal stability and tunable properties, highlighting potential applications such as adhesives. Their system's ability to recycle polymers orthogonally within mixed plastic waste streams signifies a breakthrough in chemical recycling technologies, offering scalable, energy-efficient processes that maintain polymer properties across recycling cycles, thus advancing circular economy goals for plastics [61]. Zhang et al. (2025) reviewed advances in synthesis and ignition performance of ionic liquid–hydrogen peroxide green propellants, highlighting their promise as environmentally friendly rocket fuels that combine the favorable properties of ionic liquids (such as low vapor pressure, high thermal stability, and structural tunability) with those of hydrogen peroxide (high density, low volatility, and benign decomposition). The review categorizes these propellants into self-igniting and promoter-dependent types, emphasizing the crucial role of anion-specific design and catalytic promoters for optimizing ignition delay times and combustion characteristics. The authors discussed key physicochemical parameters including viscosity, specific impulse (Isp), melting point, thermal stability, solubility, and cost, noting how these affect injector performance, combustion efficiency, and operational viability. Notably, certain promoters like ILP-18 demonstrated ultra-low ignition delay times and robust performance even at extreme temperatures, positioning them as leading candidates for next-generation green propulsion systems. The study identifies ongoing research directions involving expanding ionic liquid and promoter libraries and balancing catalytic efficacy with economic and environmental sustainability to support future aerospace propulsion applications [62].

Olawade et al. (2025) evaluated advanced AI-driven waste management technologies tailored for long-duration space missions, focusing on artificial intelligence-based sorting systems, biotechnological bioreactors, and thermal treatment methods such as plasma gasification. Their research quantitatively analyzed waste generation per crew member and assessed system energy efficiency, integration with existing life support, and implementation challenges based on experimental data from the International Space Station and terrestrial studies. Plasma arc gasification achieved up to 90% waste volume reduction but incurred high energy demands (500–1000 kWh/ton), whereas pyrolysis offered moderate waste reduction with lower energy consumption and operational complexities. Bioreactors demonstrated the lowest energy use (50–150 kWh/ton) while efficiently converting organic waste into essential resources like oxygen and water. The study also highlighted current recycling efficiencies, noting ISS water recycling rates of ~90% with potential improvements to 98%. Key challenges included microbial containment in microgravity, computational constraints for onboard AI, and high initial costs. The authors provided actionable pathways balancing energy use, recycling efficiency, and practicality to drive sustainable, autonomous waste management for future space exploration [63].

5. Nanotechnology for Energy-Efficient Aerospace Systems

5.1 Nanomaterials for Propulsion and Power

Galfetti et al. (2006) conducted an in-depth study on the use of nanoparticles, specifically aluminium powders, in solid rocket propulsion, focusing on their impact on the combustion characteristics and performance of ammonium perchlorate (AP) and hydroxyl-terminated polybutadiene (HTPB) based propellant formulations. Their research demonstrated that propellants incorporating nano-sized aluminium particles exhibit significantly higher steady burning rates compared to those with micrometric particles, primarily due to the increased specific surface area and fractal dispersion of nanoparticles which enhances the oxidation energy release near the propellant burning surface. The burning rate was found to be strongly influenced by nanoparticle size in the 0.1–0.2 µm range, while micrometric particles (~1 µm) showed negligible effect. Although nano-Al particles increase propellant density and specific impulse, challenges such as particle aggregation and agglomeration during processing and combustion remain critical, as they can reduce effectiveness. The study suggested coating nanoparticles with protective layers to prevent premature oxidation and agglomeration, representing the next frontier in nanoparticle technology for improved solid rocket propellants [48–57]

Levchenko et al. (2018) reviewed recent progress and future perspectives of space electric propulsion systems incorporating smart nanomaterials, highlighting the transformative impact of electronics miniaturization and advanced nanotechnology on small satellites and deep space missions. The authors emphasized NASA's 2015 Nanotechnology Roadmap, which advocates integrating nanomaterials and novel materials to develop adaptive, deep-space-capable spacecraft. Key advances include nanostructured materials for Hall-effect and gridded ion thrusters that enhance efficiency, durability, and operational lifetime. Self-healing concepts based on plasma-enabled nanomaterial deposition were proposed to extend thruster life by repairing wear-related damage in situ. The review also covered the role of carbon nanotubes, graphene, and nanocrystalline diamond coatings in improving channel wear resistance against plasma erosion. While highlighting challenges such as implementation complexity and weight penalties, the study underscored the potential for these nanomaterials and adaptive technologies to revolutionize electric propulsion for next-generation space exploration [49–57]

De Luca (2020) conducted a comprehensive survey on the application of nanotechnology in rocket propulsion, focusing on the use of nano-sized energetic materials (nEM) such as nanoaluminum powders in solid rocket propellants. The study traces the historical development of nEMs, highlighting their potential to enhance volumetric energy density and accelerate energy release rates compared to conventional materials. Despite promising laboratory findings, significant challenges impede their industrial-scale application, including natural inert coating on particles, non-uniform dispersion, increased slurry viscosity, handling safety, and aging effects. The work emphasizes the importance of surface modification and coating techniques to mitigate issues like particle agglomeration and spontaneous ignition. The author notes that while nanoaluminum additions can improve steady burning rates and reduce combustion product particle size, a trade-off exists due to increased sensitivity and processing complexity. De Luca underscores the need for balancing performance gains with practical constraints and safety considerations to advance nanoenergetic materials from laboratory research to large-scale rocket propulsion use [50–57]

Mohammed et al. (2025) reviewed the role of nanotechnology and artificial intelligence (AI) in optimizing thermal energy systems (TES), highlighting the significant advancements in nano-enhanced phase change materials (PCMs) and nanofluids such as Al_2O_3 and CuO, which have improved thermal conductivity by up to 28.8%, thereby accelerating energy absorption and storage. They discussed how AI algorithms, including artificial neural networks and particle swarm optimization, enable predictive modeling, real-time control, and fault detection with over 97% accuracy in complex TES operations. The review emphasized the synergistic potential of combining nanotechnology and AI to create intelligent, self-regulating TES with enhanced efficiency and sustainability, yet acknowledged challenges like computational demand, material costs, nanofluid stability, and the need for standardized testing. The authors proposed future research directions focused on economically viable nanomaterial fabrication, advanced AI model integration, and scalable solutions to support the transition to renewable energy systems with robust and optimized thermal management [51–57]

Hirankittiwong et al. (2025) provided a comprehensive review of advanced engineered nanostructures for aerospace technology, emphasizing the diverse applications of nanomaterials such as graphene, carbon nanotubes (CNTs), and metal oxide nanoparticles in power and energy systems, propulsion, thermal protection, CubeSats, and in situ resource utilization (ISRU). Their review detailed how nanocomposites enhance mechanical strength, thermal stability, and electrical properties in aerospace components, facilitating lightweight, durable structural parts and improved energy storage capabilities. They highlighted challenges including scale-up production of nanomaterials, high costs, agglomeration issues, and stability under harsh space conditions. The authors proposed innovative uses of lunar and Martian materials converted into nanoscale for ISRU applications and advanced radiation-protective materials incorporating nanomaterials for life support. They concluded that integrating nanotechnology is critical for overcoming current aerospace challenges and enabling future space exploration with enhanced performance, sustainability, and safety [52–57]

5.2 Smart Materials in Defense Applications

Singh et al. (2018) provided a comprehensive review of smart materials, classifying them into two main groups based on their responses to external stimuli: Type I materials, which convert one form of energy to another without altering their internal structure (such as piezoelectric, magneto-strictive, electro-strictive, and shape memory alloys), and Type II materials, which undergo changes in their chemical, electrical, magnetic, mechanical, or thermal properties in reaction to environmental changes (including mechanochromic and electrochromic materials). The review discussed the unique properties of smart materials, such as their ability to sense and respond to environmental changes by altering shape, size, or color, enabling applications in diverse fields such as civil and mechanical engineering, medical devices, aerospace, and stealth technology. Practical applications noted include temperature sensors, vibration dampers, self-healing components, and adaptive aerospace structures. The authors highlighted the potential of smart materials to significantly improve functionality, reliability, and efficiency across industries, pointing to ongoing research into novel applications and material enhancements as the foundation for future technological advancements [53–57]

Sharma and Srinivas (2020) reviewed the use of smart materials in the aviation industry, highlighting their critical role in developing intelligent structures that automatically adapt to environmental changes to improve operational efficiency and reduce design complexity. They discussed various smart materials including shape memory alloys (SMAs), piezoelectric materials, carbon fiber-reinforced polymers (CFRP), and shape memory polymers (SMP), emphasizing their applications in morphing aircraft components that require variable stiffness and reversible shape change. The review covered the mechanical performance, thermal responsiveness, and multifunctionality of these materials, illustrating their use in aircraft wings, aerofoils, actuators, and sensor systems. Challenges such as balancing stiffness and flexibility, fatigue resistance under fluid-structure interaction loads, and achieving cost-effective, scalable morphing technologies were identified. The authors concluded that smart materials represent a transformative advancement for aerospace engineering, enabling next-generation adaptive and efficient aircraft designs [54–57].

Madake et al. (2021) reviewed the state of the art of smart materials for defense applications, highlighting their ability to adapt and change properties in response to environmental stimuli such as stress, moisture, electric or magnetic fields, light, temperature, and pH. The review classified smart materials broadly into active and passive types, including shape memory alloys, piezoelectric materials, electrostrictive, magnetostrictive, rheological, thermo-responsive, electrochromic, biomimetic materials, and smart gels. These materials find significant applications across aerospace, defense, automotive, healthcare, and civil engineering sectors. Specifically, in defense, smart materials are employed for ballistic protection, self-healing uniforms, integrated protective gear, chemical and biological threat protection, and counter-surveillance through advanced textile systems. The authors emphasized the versatility, self-repair capability, and multifunctionality of smart materials as critical to advancing modern defense technologies, while also acknowledging ongoing challenges related to manufacturing quality, integration, and cost-effectiveness [55–57]

Siengchin (2023) reviewed the present and future developments of lightweight materials for defense applications, emphasizing their critical role in enhancing the strength-to-weight ratio, thermal resistance, radiation resistance, fatigue durability, and damage tolerance of defense equipment. The review discussed various lightweight composites including metal matrix composites (MMCs), polymer matrix composites (PMCs), ceramic matrix composites (CMCs), and fiber composites widely used across aerospace and defense sectors for applications such as rocket engine parts, aircraft body structures, and combat vehicle armor. Future trends highlighted include the incorporation of nanotechnology for developing advanced sensor materials, electromagnetic interference shielding, corrosion detection, and radiation protection. Despite the benefits, challenges such as high production costs and integration with existing systems remain, and further research is recommended to optimize recyclability and cost-effectiveness, ensuring these materials continue to advance defense technology capabilities [56,57]

Wang et al. (2023) reviewed the development and prospects of smart materials and structures for aerospace sensing systems, focusing on piezoelectric materials, shape memory materials, and giant magneto strictive materials as key smart materials in the aviation industry. The review highlighted the unique physical and integration properties of these materials, making them ideal for applications such as structural health monitoring, energy harvesting, vibration and noise control, damage mitigation, and high-precision actuation. Piezoelectric materials are extensively researched for their bi-directional electromechanical behavior and roles in sensing and actuation, while shape memory materials offer outstanding performance in shape control, vibration damping, and self-healing structures. Giant magneto strictive materials exhibit high-resolution output and are gaining attention for guided wave monitoring and micro-vibration control. The paper emphasized ongoing advances toward smarter, more robust, and multifunctional aerospace systems with improvements in nonlinear composite control techniques for enhanced safety and longevity [57].

6. Conclusion

The present review demonstrates that green monopropellants and bipropellants, smart energetic formulations, and advanced fuel cell technologies have collectively reached a level of technological maturity at which they can no longer be regarded as niche alternatives, but rather as key enablers of the next generation of space transportation and infrastructure. Across the literature, environmentally benign oxidizers such as hydrogen peroxide and nitrous oxide, ionic liquid–based hypergols, metal and metal–boride nanocomposites, and electrically controlled solid propellants exhibit performance metrics that are competitive with, and in several cases superior to, legacy hydrazine- and nitrogen tetroxide-based systems, while substantially lowering operational toxicity and ground-handling complexity. In parallel, regenerative hydrogen–oxygen fuel cells and integrated RFC architectures provide high specific energy, strong functional coupling with life support, and compelling mass advantages over purely battery-based storage for long-duration and high-autonomy missions, especially when combined with emerging closed-loop water, oxygen, and carbon management schemes.

References

[1] C. Scharlemann, Green Propellants: Global Assessment of Suitability and Applicability, 3rd Eur. Conf. Aero-Sp. Sci. (2009) 1–17.

[2] S.S. Shekhawat, Review Paper on Green Propulsion Technologies for Spacecraft : A Comprehensive Survey, Int. J. Res. Anal. Rev. 5 (2018) 115–121.

[3] A.A. Satheesan, I.G. V Patil, S. Pragadheswaran, GREEN PROPULSION : AN EMERGING TECHNOLOGY IN SPACE, Int. J. Innov. Res. Multidiscip. F. 7 (2021) 107–111.

[4] I. Verma, D. Dhalla, S. Jain, S. Pal, GREEN PROPELLANT : A REVIEW, J. Emerg. Technol. Innov. Res. 11 (2024) 378–385.

[5] A. Sarritzu, A. Pasini, Performance comparison of green propulsion systems for future Orbital Transfer Vehicles, Acta Astronaut. 217 (2024) 100–115. https://doi.org/10.1016/j.actaastro.2024.01.032.

[6] L. Blondel-Canepari, A. Sarritzu, A. Pasini, A holistic approach for efficient greener in-space propulsion, Acta Astronaut. 223 (2024) 435–447. https://doi.org/10.1016/j.actaastro.2024.07.023.

[7] M. Kurilov, C.U. Kirchberger, S. Schlechtriem, Characterization of an Ignition System for Nitromethane-Based Monopropellants †, Aerospace 11 (2024). https://doi.org/10.3390/aerospace11121001.

[8] S.M. Choi, S. Jung, V.M.P. Ugolini, S. Kwon, Combustion Visualization and Liquid Jet in Crossflow Analysis of H2O2/Kerosene Bipropellant Thruster, Aerospace 12 (2025). https://doi.org/10.3390/aerospace12020110.

[9] S. Lee, V.M.P. Ugolini, E. Jung, S. Kwon, Demonstration of Polyethylene Nitrous Oxide Catalytic Decomposition Hybrid Thruster with Dual-Catalyst Bed Preheated by Hydrogen Peroxide, Aerospace 12 (2025) 1–12. https://doi.org/10.3390/aerospace12020158.

[10] J. Han, M. Wen, Y. Hong, B. Du, L. Jiang, H. Cui, G. Feng, J. Song, Theoretical Research on the Combustion Characteristics of Ammonium Dinitramide-Based Non-Toxic Aerospace Propellant, Aerospace 12 (2025). https://doi.org/10.3390/aerospace12040295.

[11] Z. Gut, A. Parzybut, D. Perigo, Development of a Throttleable 6 kN H2O2/Butyl Alcohol Rocket Engine, Aerospace 12 (2025) 1–17. https://doi.org/10.3390/aerospace12070617.

[12] V.K. Bhosale, K. Lee, V.M.P. Ugolini, H. Yoon, Investigation of Combustion Performance of Hypergolic Ionic Liquid Fuels Through Injector Design, Aerospace 12 (2025) 1–12. https://doi.org/10.3390/aerospace12090759.

[13] A. Okninski, P. Surmacz, K. Sobczak, W. Florczuk, D. Cieslinski, A. Gorgeri, B. Bartkowiak, D. Kublik, M. Ranachowski, Z. Gut, A. Parzybut, A. Kasztankiewicz, J. Mazurek, F. Valencia Bel, A. Herbertz, K. Underhill, D. Schneider, A. Flock, Development of Green Bipropellant Thrusters and Engines Using 98% Hydrogen Peroxide as Oxidizer, Aerospace 12 (2025) 879. https://doi.org/10.3390/aerospace12100879.

[14] A. Algharrash, A. Alomairi, H. Althaydi, E. Alnafisah, Green Propulsion Technologies for Sustainable Space Operation Advancments , Applications , and Future Prospects Green Propulsion Technologies for Sustainable Space Operation Advancments , Applications , and Future Prospects, in: 76th Int. Astronaut. Congr., Copyright ©2025 by the International Astronautical Federation, Sydney, 2025: pp. 1–20.

[15] K.A. Burke, Fuel cells for space science applications, 1st Int. Energy Convers. Eng. Conf. IECEC (2003). https://doi.org/10.2514/6.2003-5938.

[16] A.X. Zhang, T. Ylikorpi, G. Pepe, Biomass-based Fuel Cells for Manned Space Exploration Final Report Biomass-based Fuel Cells for Manned Space Exploration, Fuel Cells 31 (2005). http://www.esa.int/act.

[17] K. Krishen, New technology innovations with potential for space applications, Acta Astronaut. 63 (2008) 324–333. https://doi.org/10.1016/j.actaastro.2007.12.047.

[18] J. Garche, L. Jörissen, Applications of fuel cell technology: Status and perspectives, Electrochem. Soc. Interface 24 (2015) 39–43. https://doi.org/10.1149/2.F02152if.

[19] A.R. Jha, Next-generation batteries and fuel cells for commercial, military, and space applications, 2016. https://doi.org/10.1201/b12152.

[20] J. Brey, D. Muñoz, V. Mesa, T. Guerrero, Use of Fuel Cells and Electrolyzers in Space Applications: From Energy Storage to Propulsion/Deorbitation, E3S Web Conf. 16 (2017). https://doi.org/10.1051/e3sconf/20171617004.

[21] Q. Guo, F. Ye, H. Guo, C.F. Ma, Gas/Water and Heat Management of PEM-Based Fuel Cell and Electrolyzer Systems for Space Applications, Microgravity Sci. Technol. 29 (2017) 49–63. https://doi.org/10.1007/s12217-016-9525-6.

[22] G. Giacoppo, S. Hovland, O. Barbera, 2 kW Modular PEM fuel cell stack for space applications: Development and test for operation under relevant conditions, Appl. Energy 242 (2019) 1683–1696. https://doi.org/10.1016/j.apenergy.2019.03.188.

[23] D. Akinyele, E. Olabode, A. Amole, Review of fuel cell technologies and applications for sustainable microgrid systems, Inventions 5 (2020) 1–35. https://doi.org/10.3390/inventions5030042.

[24] N.A.A. Qasem, G.A.Q. Abdulrahman, A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications, Int. J. Energy Res. 2024 (2024). https://doi.org/10.1155/2024/7271748.
[25] K. Sharma, A. Santasalo-Aarnio, Energy storage systems for space applications, J. Energy Storage 128 (2025) 117131. https://doi.org/10.1016/j.est.2025.117131.
[26] S. Belz, A synergetic use of hydrogen and fuel cells in human spaceflight power systems, Acta Astronaut. 121 (2016) 323–331. https://doi.org/10.1016/j.actaastro.2015.05.031.
[27] M.C. Guzik, I.J. Jakupca, R.P. Gilligan, W.R. Bennett, P.J. Smith, J. Fincannon, Regenerative fuel cell power systems for lunar and martian surface exploration, AIAA Sp. Astronaut. Forum Expo. Sp. 2017 0 (2017) 1–18. https://doi.org/10.2514/6.2017-5368.
[28] H. Sun, W. Pei, Y. Dong, H. Yu, S. You, Proceedings of the 10th World Hydrogen Technology Convention, Springer Proceedings in Physics, 2023.
[29] L. Feng, J. Wang, W. Xie, C. Wen, S. Li, Q. Cui, C. Wan, Y. Zhao, Research on integrated energy system of fuel cells for space application, J. Phys. Conf. Ser. 2840 (2024). https://doi.org/10.1088/1742-6596/2840/1/012002.
[30] M.S. Glascock, J.L. Rovey, K.A. Polzin, Performance Measurements of Electric Solid Propellant in an Ablative Pulsed Electric Thruster, Https://Ntrs.Nasa.Gov/Citations/20190030421 (2019) 1–4.
[31] W. Zhang, H. Xie, Z. Wang, L. Bao, R. Shen, Design , fabrication and characterization of electrically controlled solid microthruster, (2023) 8–12. https://doi.org/10.13009/EUCASS2023-711.
[32] Z. Wang, F. Li, Q. Zhang, L. Li, K. Ouyang, R. Shen, Y. Ye, L.T. DeLuca, W. Zhang, Electrically controlled solid chemical propulsion: A review, Chem. Eng. J. 496 (2024) 154100. https://doi.org/10.1016/j.cej.2024.154100.
[33] Y. Li, H.Y. Lv, S.W. Song, Q.L. Yan, Q.H. Zhang, Recent advances on electrically controlled solid propellants, Fuel 394 (2025) 135096. https://doi.org/10.1016/j.fuel.2025.135096.
[34] D.E. Montr, R. Jos, P. Lima, P. De, N.I.E. Chimique, C.P.D.E. Montr, A.L. Th, S.E. Pr, E.N.V.U.E. De, O.D.U. Dipl, M.E.D.E.P. Doctor, N.I.E. Chimique, R. Jos, P. Lima, Synthesis of Metal-Polymer Nanocomposites for Fuel Applications Synthesis of Metal-Polymer Nanocomposites for Fuel, (2015).
[35] T. Manning, R. Field, K. Klingaman, M. Fair, J. Bolognini, R. Crownover, C.P. Adam, V. Panchal, E. Rozumov, H. Grau, P. Matter, M. Beachy, C. Holt, S. Sopok, Innovative boron nitride-doped propellants, Def. Technol. 12 (2016) 69–80. https://doi.org/10.1016/j.dt.2015.10.001.
[36] R. Grosjean, M.M. Denis, Boron-based nanomaterials under extreme conditions, (2018).
[37] N. Xiao, Z. Wang, Y. Yin, K. Yang, D. Zhao, H. Chen, Y. Wang, Y. Shi, Z. Liu, Y. Huo, Environmental Applications of Hexagonal Boron Nitride Nanomaterials: Structure, Properties, and Future Perspectives, Adv. Mater. Technol. n/a (2025) e01475. https://doi.org/https://doi.org/10.1002/admt.202501475.
[38] S.D. Nehate, A.K. Saikumar, A. Prakash, K.B. Sundaram, A review of boron carbon nitride thin films and progress in nanomaterials, Mater. Today Adv. 8 (2020) 100106. https://doi.org/10.1016/j.mtadv.2020.100106.
[39] R.Y. Tay, H. Li, H. Wang, J. Lin, Z.K. Ng, R. Shivakumar, A. Bolker, M. Shakerzadeh, S.H. Tsang, E.H.T. Teo, Advanced nano boron nitride architectures: Synthesis, properties and emerging applications, Nano Today 53 (2023) 102011. https://doi.org/10.1016/j.nantod.2023.102011.
[40] M.G. Gök, Ö. Cihan, M. Guven Gok, O. Cihan, Energetic Materials and Metal Borides for Solid Propellant Rocket Engines, Int. J. Mater. Eng. Technol. 003 (2020) 109–119. http://dergipark.gov.tr/tijmet.
[41] W. Pang, Y. Li, L.T. Deluca, D. Liang, Z. Qin, X. Liu, H. Xu, X. Fan, Effect of metal nanopowders on the performance of solid rocket propellants: A review, Nanomaterials 11 (2021). https://doi.org/10.3390/nano11102749.
[42] G. Singh, X. Gui, D. Torres, commercial success Modeling of Combustion Processes Improves Engine Efficiency Background, Commer. Success (2006). www.eere.energy.gov.
[43] O.M. Cala, L. Meriño, V. Kafarov, J. Saavedra, Evaluation of combustion models for determination of refinery furnaces efficiency Evaluación de modelos de combustión para la determinación de la eficiencia en hornos de refinería, Ingeniare. Rev. Chil. Ing. 23 (2015) 429–438.
[44] A.K. Azad, M.G. Rasul, M.M.K. Khan, S.C. Sharma, M.M.K. Bhuiya, Recent development of biodiesel combustion strategies and modelling for compression ignition engines, Renew. Sustain. Energy Rev. 56 (2016) 1068–1086. https://doi.org/10.1016/j.rser.2015.12.024.
[45] D. Zhou, W. Yang, J. Li, K.L. Tay, S.K. Chou, M. Kraft, Efficient Combustion Modelling in RCCI Engine with Detailed Chemistry, Energy Procedia 105 (2017) 1582–1587. https://doi.org/10.1016/j.egypro.2017.03.504.
[46] M. Pelosin, R. Novella, G. Bracho, C. Fernandes, T. Lucchini, L. Marmorini, Q. Zhou, Combustion Modeling Approach for the Optimization of a Temperature Controlled Reactivity Compression Ignition Engine Fueled with Iso-Octane, Energies 15 (2022). https://doi.org/10.3390/en15218216.

[47] O.G. Glotov, V.A. Poryazov, G.S. Surodin, I. V. Sorokin, D.A. Krainov, Combustion features of boron-based composite solid propellants, Acta Astronaut. 204 (2023) 11–24. https://doi.org/10.1016/j.actaastro.2022.12.024.

[48] L. Galfetti, L.T. De Luca, F. Severini, L. Meda, G. Marra, M. Marchetti, M. Regi, S. Bellucci, Nanoparticles for solid rocket propulsion, J. Phys. Condens. Matter 18 (2006). https://doi.org/10.1088/0953-8984/18/33/S15.

[49] I. Levchenko, S. Xu, G. Teel, D. Mariotti, M.L.R. Walker, M. Keidar, Recent progress and perspectives of space electric propulsion systems based on smart nanomaterials, Nat. Commun. 9 (2018). https://doi.org/10.1038/s41467-017-02269-7.

[50] L.T. DeLuca, A survey of nanotechnology for rocket propulsion: Promises and challenges, ELSI Handb. Nanotechnol. Risk, Safety, ELSI Commer. (2020) 277–332. https://doi.org/10.1002/9781119592990.ch12.

[51] H.I. Mohammed, F.L. Rashid, H. Togun, E.B. Agyekum, A. Ameen, K.A. Hammoodi, R. Parveen, S.A. Kadhim, W.N. Abbas, The role of nanotechnology and artificial intelligence in optimizing thermal energy systems, Appl. Energy 400 (2025) 126576. https://doi.org/10.1016/j.apenergy.2025.126576.

[52] P. Hirankittiwong, T. Chomchok, S. Chakraborty, P. Prajongtat, D.P. Singh, N. Hongkarnjanakul, S. Channumsin, S. Ghosh, N. Chattham, Advanced engineered nanostructures for aerospace technology: A review, Results Eng. 26 (2025). https://doi.org/10.1016/j.rineng.2025.105381.

[53] M. Singh, R.K. Sharma, A.K. Singh, N. Prajapati, A Study of Smart Materials, Classification and Applications : A Review, Int. J. Manag. Technol. Eng. 8 (2018) 412–420.

[54] K. Sharma, G. Srinivas, Flying smart: Smart materials used in aviation industry, Mater. Today Proc. 27 (2020) 244–250. https://doi.org/10.1016/j.matpr.2019.10.115.

[55] H.A. Madake, Y.A. Fakir, S.S. Bhanuse, C.R. Shinagare, K.S. Pirjade, A.S.N. Husainy, A Review on the State of Art of Smart Material for Defence Applications, Int. J. Trend Sci. Res. Dev. 5 (2021) 1448–1453.

[56] S. Siengchin, A review on lightweight materials for defence applications: Present and future developments, Def. Technol. 24 (2023) 1–17. https://doi.org/10.1016/j.dt.2023.02.025.

[57] W. Wang, Y. Xiang, J. Yu, L. Yang, Development and Prospect of Smart Materials and Structures for Aerospace Sensing Systems and Applications, Sensors 23 (2023) 1–28. https://doi.org/10.3390/s23031545.