Acceleron Aerospace Journal || AAJ.11.2106-2441
Volume 3, Issue 2, pp (451-458)
Review Paper
E-ISSN- 2583-9942 || DOI: 10.61359/11.2106-2441

Fueling the Future: Innovative Methods for Generating Emergency Fuel in Rockets

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Abstract: As humanity advances toward ambitious space missions, including Mars exploration, lunar bases, and deep space travel, the need for reliable and sustainable emergency fuel sources becomes paramount. This article, "Fueling the Future: Innovative Methods for Generating Emergency Fuel in Rockets," investigates cutting-edge approaches to rocket fuel generation that address the challenges of traditional methods. It explores a range of innovative techniques, from advanced propulsion systems utilizing in-situ resource utilization to the development of biofuels derived from renewable sources. The review highlights specific microorganisms used in bioreactors for emergency fuel generation, including their production rates, yields, and recent technological advancements. Additionally, it examines photocatalysts for solar-to-fuel technologies, analyzing their efficiencies and potential for converting sunlight into rocket fuels. The article also discusses ammonia as an alternative fuel source, considering its energy density, combustion challenges, and potential in fuel cells for space applications. By providing a comprehensive overview of these emerging technologies, this article aims to illuminate the future of rocket fuel innovation, enhancing mission safety and advancing sustainable space exploration.

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1. Introduction

In the world of rocketry, where precision and reliability are paramount, the need for emergency fuel has emerged as a critical consideration. With increasing exploration into space and missions venturing deeper into the cosmos, the stakes couldn't be higher. Emergency fuel acts as an insurance policy, giving spacecraft a second chance at navigating unforeseen challenges or malfunctions, such as trajectory deviations, equipment failures, or providing the extra push needed to safely return to Earth. A recent incident involving Sunita Williams and her team highlights the importance of emergency fuel and the need to prioritize the safety aspects of rockets to ensure a safe return. Traditionally, the focus has been on primary fuel sources, often overlooking the necessity of a robust emergency fuel strategy. However, the complexities of modern rocketry demand innovative solutions that prioritize safety without compromising mission integrity. From the development of compact, high-energy fuels that can be efficiently stored for quick access, to advanced propulsion systems that allow for rapid fuel deployment, the industry is witnessing a paradigm shift. Moreover, as we strive for sustainable space exploration, the quest for eco-friendly emergency fuel options has taken center stage. Researchers are exploring alternative sources such as biofuels or even in-situ resource utilization (ISRU), which harnesses materials found on other celestial bodies to create fuel on demand. These developments not only enhance mission safety but also align with broader goals of reducing environmental impact and promoting the sustainability of space travel [1].

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** Received: 15-August-2024 || Revised: 29-August-2024 || Accepted: 29-August-2024 || Published Online: 30-August-2024.

2. Significance of Rocket Fuel Reliability in Space Missions

In space missions, the reliability of fuel is not just a technical consideration—it's a matter of life and death. The stakes are incredibly high; even the smallest oversight in fuel management can lead to catastrophic failures, jeopardizing both the mission and the lives of astronauts onboard. As we venture deeper into the cosmos, the importance of reliable fuel sources becomes even more pronounced. Reliable fuel ensures that spacecraft can complete their missions, whether reaching orbit, docking with the International Space Station, or embarking on exploratory journeys to distant planets. Each stage of a rocket's flight relies on precise fuel delivery and combustion, making it critical to select fuel that can withstand the extreme conditions of space, such as fluctuating temperatures and vacuum environments. The challenges of fuel reliability are compounded by the sheer complexity of space missions. For example, during multi-stage launches, different types of fuel may be required at different phases, each needing to perform flawlessly under varying conditions. It's not just about having fuel that burns efficiently; it's about having a comprehensive understanding of how that fuel interacts with the rocket's systems and the environments it will encounter. In this context, innovative methods of generating emergency fuel become invaluable. As we look to the future, investing in research and development of emergency fuel generation methods will be integral to ensuring that our journeys into space are both safe and successful [2].

3. Unique Method to Generate Rocket Fuel

In the realm of rocket science, where precision and reliability are non-negotiable, the quest for innovative methods of generating emergency fuel has garnered significant attention. As missions to explore deeper into space gain momentum, the need for a dependable fuel source in unforeseen circumstances becomes paramount. Traditional fuel reserves may not always be accessible, particularly during long-duration missions far from Earth. One promising avenue is the utilization of in-situ resource utilization (ISRU), which involves harnessing local resources to produce fuel. For missions to Mars or the Moon, this could mean extracting water ice from the lunar regolith or Martian soil. Through processes like electrolysis, water can be split into hydrogen and oxygen—key components for rocket fuel. This not only provides an emergency fuel supply but also significantly reduces the payload weight during initial launches. Another innovative method gaining traction involves the use of bioreactors. Researchers are investigating the potential of genetically engineered microorganisms that can produce hydrocarbons or alcohol-based fuels from carbon dioxide and sunlight. This biological approach offers a sustainable way to generate fuel in space, tapping into the abundant CO2 found in the atmospheres of other planets or even recycling waste products from astronauts' habitats.

Moreover, advancements in battery technology might lead to the development of hybrid propulsion systems. These systems could allow rockets to utilize stored energy from batteries to power secondary propulsion systems if primary fuel sources become compromised. This redundancy could be crucial during critical phases of a mission where every second counts. Lastly, the concept of compact fuel cells is emerging as a viable option for generating emergency power. Fuel cells convert chemical energy directly into electricity, and when designed with portable hydrogen or methanol supplies, they could serve as an invaluable backup system for spacecraft during emergencies. As we continue to push the boundaries of space exploration, innovative methods for generating emergency fuel are not just enhancing mission safety; they are paving the way for a future where humanity can thrive beyond our home planet. Here, we explore some methods to generate emergency fuel.

4. Methods to Produce Rocket Fuel

4.1. Utilizing Electrolysis for Hydrogen Production

Electrolysis for hydrogen production stands as a pioneering approach in aerospace engineering, offering a sustainable and efficient method for generating emergency rocket fuel. The process involves the dissociation of water (H_2O) into its constituent elements—hydrogen (H_2) and oxygen (O_2)—through the application of an electrical current. This technology not only provides a reliable fuel source but also aligns with the increasing demand for environmentally friendly solutions within the aerospace sector. In the context of space exploration, the ability to generate fuel on-demand can be mission-critical, particularly in emergency scenarios where traditional fuel reserves may be depleted or unavailable. The versatility of electrolysis lies in its potential to utilize water from extraterrestrial sources, such as lunar or Martian ice, making it an ideal candidate for long-duration missions. The process is relatively straightforward: an electric current applied to water results in the production of hydrogen and oxygen gases, which can be stored separately for use in propulsion systems. Hydrogen serves as a potent fuel, while oxygen can function as an oxidizer, enhancing the overall efficiency of the system. This method is integral to advancing the resilience and adaptability of space missions, particularly in environments where traditional fuel supplies are not feasible. By leveraging local resources and cutting-edge technology, electrolysis not only ensures mission safety but also fosters the sustainability of interplanetary exploration. Recent research into various electrolysis systems has demonstrated significant improvements in efficiency, further solidifying the viability of this technology for aerospace applications [2-5].

4.1.1 Types of Electrolysis Systems

There are several types of electrolysis systems, each with unique advantages and challenges. Alkaline Electrolysis (AEL) is a mature technology characterized by an efficiency range of 60-70% under typical operating conditions with liquid alkaline electrolytes such as potassium hydroxide (KOH). Despite its established use, AEL faces challenges, including lower efficiency and slower response times. Proton Exchange Membrane (PEM) Electrolysis offers higher efficiency, ranging from 65-80%, with the benefit of a rapid dynamic response and a compact design. However, PEM systems are costlier due to the use of precious metal catalysts, like platinum. Solid Oxide Electrolysis Cells (SOEC) present the highest efficiency potential, reaching up to 85-90%, particularly in high-temperature environments where waste heat can be effectively utilized. However, the high operating temperatures of 700-1000°C pose significant material stability challenges. Anion Exchange Membrane (AEM) Electrolysis, a developing technology, targets efficiencies of 70-80% by combining the benefits of both PEM and AEL systems, although scalability and long-term stability remain areas of active research [2-5].

4.1.2 Specific Research Examples

Recent advances in high-temperature electrolysis have demonstrated efficiencies exceeding 90%, particularly when SOECs are integrated with nuclear power, utilizing excess heat to maximize overall system efficiency. For instance, research conducted at the Idaho National Laboratory highlights SOECs' potential in large-scale hydrogen production with minimal energy loss. Meanwhile, PEM electrolysis, when coupled with renewable energy sources such as solar power, has shown nearly 80% efficiency, according to studies by the Fraunhofer Institute for Solar Energy Systems. This synergy between PEM electrolyzers and renewable energy presents a promising avenue for emergency hydrogen fuel generation. Additionally, ongoing developments in AEM electrolysis at the National Renewable Energy Laboratory have achieved efficiency rates around 70%, with a focus on improving the scalability and cost-effectiveness of this emerging technology.

4.2. Bioreactors: Harnessing Microorganisms for Fuel Generation

Bioreactors represent a cutting-edge solution in the pursuit of sustainable and efficient rocket fuel production. These sophisticated systems exploit the metabolic capabilities of microorganisms, such as bacteria, algae, and yeast, to convert organic materials into biofuels. This approach offers a renewable alternative to conventional rocket propellants, aligning with the global shift towards greener technologies in aerospace engineering. In essence, bioreactors function as miniature factories, where microorganisms metabolize substrates like agricultural waste, carbon dioxide, and wastewater into energy-rich compounds. These compounds, including bioethanol, biobutanol, and methane, can be harnessed as propellants for rocket engines. The adaptability of bioreactors is a significant advantage, as the production rates and yields of specific fuels can be optimized by adjusting factors such as temperature, pH, and nutrient availability. This flexibility makes bioreactors particularly valuable for space missions, where the ability to produce fuel on-demand can reduce the logistical challenges associated with fuel storage and transportation. The utilization of bioreactor-generated fuels could revolutionize mission planning, enabling more flexible and sustainable designs. By integrating bioreactors with in-situ resource utilization (ISRU) strategies, it may become possible to produce fuel directly on other planets, further reducing dependence on Earth-based resources. The potential for such systems to contribute to waste management and carbon sequestration adds another layer of environmental benefit, making bioreactors a promising technology for the future of space exploration [5-6].

4.2.1. Microorganisms Used in Bioreactors

The efficiency of bioreactors in producing rocket fuels hinges on the specific microorganisms employed. For instance, genetically engineered *Escherichia coli* (E. coli) has shown promise in producing isopropanol, a precursor for isopropyl nitrate, with production rates of 1.1 g/L/h and yields approaching 90% of the theoretical maximum. Similarly, *Clostridium acetobutylicum* is utilized in acetone-butanol-ethanol (ABE) fermentation to produce butanol, a key component of butyl nitrate, with production rates of 0.78 g/L/h and yields of 0.3 g/g glucose. *Rhodobacter sphaeroides*, a photosynthetic bacterium, has demonstrated the ability to produce hydrogen gas under anaerobic and light conditions, with production rates of 0.045 mmol H_2/L/h and yields of 0.15 mol H_2/mol glucose. Additionally, *Saccharomyces cerevisiae* (yeast) is widely used for ethanol production, achieving rates of 2.0 g/L/h and yields of 0.51 g/g glucose **[6-7]**.

4.2.2. Recent Advances and Challenges

Significant progress has been made in optimizing the metabolic pathways and culture conditions of these microorganisms to enhance fuel production. For example, genetic modifications in E. coli have led to a 30% increase in isopropanol yields by knocking out competing pathways and overexpressing key enzymes. Advances in bioreactor design, such as the implementation of continuous stirred-tank reactors (CSTRs) and fed-batch cultures, have improved butanol production in C. acetobutylicum, maintaining optimal pH and nutrient levels. The integration of photobioreactors with solar energy systems has also shown potential in scaling up hydrogen production from R. sphaeroides, although challenges remain in optimizing light exposure and bacterial growth conditions.The use of microorganisms in bioreactors offers a viable pathway for sustainable rocket fuel production. While considerable advancements have been made, ongoing research is crucial to further optimize production rates, improve yields, and integrate these systems with renewable energy sources. This research will be instrumental in ensuring the scalability and sustainability of bioreactor-based fuel generation for space missions **[7]**.

4.3. Solar-to-Fuel Technologies: Converting Sunlight into Rocket Fuel

As we venture further into the cosmos, the need for sustainable and efficient fuel sources becomes increasingly critical. Solar-to-fuel technologies stand at the forefront of this innovation, offering a revolutionary approach to fuel generation that taps into one of our most abundant resources: sunlight. These processes harness solar energy to convert carbon dioxide and water into usable fuels, such as hydrogen or hydrocarbons, which can then be utilized in rocket propulsion systems. At the heart of solar-to-fuel technologies is the concept of artificial photosynthesis, mimicking the natural process by which plants convert sunlight into energy. Advanced materials, such as photo catalysts or photo voltaics combined with electro catalysis, play a vital role in this transformation. These materials capture solar radiation and facilitate chemical reactions that break down water molecules to release hydrogen or combine carbon dioxide with hydrogen to create synthetic hydrocarbons.

One of the most promising aspects of solar-to-fuel technologies is their potential to be deployed in extra-terrestrial environments. Imagine a future where rockets can generate their fuel on Mars or the Moon using local resources—solar energy from the sun and CO2 from the atmosphere or regolith. This capability not only reduces the need to transport fuel from Earth, significantly lowering mission costs, but also enhances the sustainability of long-term space exploration. The direct conversion of sunlight into chemical fuels using photocatalysts has garnered significant interest as a sustainable approach to generating rocket fuels. This process, known as solar-to-fuel technology, leverages photocatalysts to drive reactions that produce high-energy fuels from sunlight, water, and carbon dioxide. The below exploration delves into specific photocatalysts, their efficiencies, and recent advancements in converting sunlight into rocket fuels, supported by data from current research.

4.3.1. Key Photocatalysts in Solar-to-Fuel Technologies

1) Titanium Dioxide (TiO_2)

- ***Application:*** TiO_2 is one of the most studied photocatalysts for water splitting to produce hydrogen, a potential rocket fuel.
- ***Efficiency:*** Photocatalytic efficiency of TiO_2 for hydrogen production has been reported at around 1-2% under UV light (Chen & Mao, 2007).
- ***Recent Advances:*** Doping TiO_2 with non-metals like nitrogen or carbon has been shown to extend its light absorption into the visible spectrum, improving efficiency to around 5% (Zhao et al., 2018).

2) Bismuth Vanadate ($BiVO_4$)

- ***Application:*** $BiVO_4$ is a promising photocatalyst for oxygen evolution reactions (OER) in water splitting, which is critical for sustainable hydrogen production.
- ***Efficiency:*** $BiVO_4$ has achieved solar-to-hydrogen conversion efficiencies of approximately 4.9% in tandem with a suitable hydrogen evolution catalyst (Kim & Choi, 2014).
- ***Recent Advances:*** The integration of co-catalysts like cobalt phosphate (Co-Pi) with $BiVO_4$ has further enhanced its efficiency, reaching up to 6.3% under optimized conditions (Li et al., 2020).

3) Copper-Zinc-Tin-Sulfide (CZTS)

- ***Application:*** CZTS has emerged as a promising material for CO_2 reduction, converting it into hydrocarbons like methane or methanol, which can be used as rocket fuels.
- ***Efficiency:*** The conversion efficiency of CZTS for CO_2 reduction has been reported at 2.1% for methane production (Li et al., 2018).
- ***Recent Advances:*** Modifications to the surface structure and the introduction of plasmonic nanoparticles have improved the selectivity and overall efficiency of CZTS, with reported solar-to-fuel efficiencies of up to 3.5% for methanol production (Wang et al., 2021).

4) Cobalt Phosphide (CoP)

- ***Application:*** CoP is utilized as a co-catalyst in conjunction with other photocatalysts like TiO_2 or $BiVO_4$ to enhance hydrogen evolution reactions (HER).
- ***Efficiency:*** CoP has been shown to increase the photocatalytic hydrogen production efficiency by up to 2.5 times when used with TiO_2 under simulated sunlight, achieving an overall solar-to-hydrogen conversion efficiency of approximately 6% (Tao et al., 2019).
- ***Recent Advances:*** The synthesis of nanostructured CoP has led to further improvements in catalytic activity, with reports of up to 7% efficiency in integrated systems (Yang et al., 2022).

4.3.2. Analysis of Efficiency and Scalability

Efficiency Trends

- The efficiencies of photocatalysts for solar-to-fuel conversion remain modest compared to conventional solar photovoltaic technologies. However, ongoing research is steadily improving these figures, with several photocatalysts now achieving efficiencies in the 5-7% range under optimal laboratory conditions.
- Advances in nanotechnology, doping, and the development of hybrid systems that combine multiple photocatalysts or co-catalysts are critical to enhancing overall efficiency. For example, the combination of $BiVO_4$ with CoP has shown significant synergistic effects, leading to higher solar-to-fuel conversion rates (Li et al., 2020; Tao et al., 2019).

Challenges in Scaling Up

- Scaling up solar-to-fuel technologies from laboratory settings to industrial applications faces significant challenges, including the stability of photocatalysts, cost of materials, and the integration of these systems with existing energy infrastructures.
- Long-term stability under continuous sunlight exposure is a critical factor, as many photocatalysts degrade over time, reducing efficiency. Research is focused on developing more robust materials that maintain high performance over extended periods (Yang et al., 2022).

Potential for Rocket Fuel Production

The production of hydrogen and hydrocarbons such as methane or methanol through solar-to-fuel technologies holds great potential for rocket fuel applications. Hydrogen, in particular, is already a well-established rocket fuel, and improvements in photocatalytic water splitting could provide a sustainable source for emergency fuel generation.

Methanol produced from CO_2 reduction can be further processed into dimethyl ether (DME), a promising rocket propellant, highlighting the versatility of these technologies in generating various forms of rocket fuel.

4.4. The Role of Ammonia as an Emergency Fuel Source

Ammonia (NH_3), a compound predominantly used in agriculture and industry, is gaining attention as a potential emergency fuel source for rockets. Its chemical composition, consisting of nitrogen and hydrogen, along with its availability and ability to be produced from renewable resources, makes ammonia an appealing alternative to traditional rocket fuels. In the context of aerospace engineering, ammonia's properties present unique advantages and challenges, particularly in scenarios where emergency fuel supplies are critical. A key advantage of ammonia as a rocket fuel is its high energy density, which is crucial for emergency situations where maximizing fuel efficiency and minimizing weight are paramount. Unlike cryogenic fuels that require complex storage systems, ammonia can be stored at ambient temperatures and pressures, simplifying the fuel handling process and enhancing operational safety. These characteristics make ammonia a practical choice for missions where rapid response and reliability are essential.

In terms of propulsion, ammonia can be utilized in two main ways: through combustion or in fuel cells. Combustion of ammonia produces energy while releasing nitrogen and water vapor, which results in a lower environmental impact compared to conventional hydrocarbon fuels. Alternatively, ammonia can be used in fuel cells, where it reacts with oxygen to generate electricity, offering an innovative method for powering electric propulsion systems. This dual potential for ammonia underscores its versatility as an emergency fuel source in space exploration. As the aerospace industry continues to prioritize sustainability, ammonia's role as an emergency fuel could become increasingly significant. Its use not only provides a reliable solution for unexpected scenarios but also aligns with broader efforts to reduce the environmental impact of space missions.

4.4.1 Energy Density Comparisons

Ammonia's energy density is a critical factor in its consideration as a rocket fuel. When evaluated against other fuels, ammonia shows distinct advantages and limitations depending on the specific application. For instance, ammonia's volumetric energy density is 11.5 MJ/L, which is lower than that of RP-1 (35 MJ/L) and methane (22.2 MJ/L) but comparable to liquid hydrogen (8.5 MJ/L). However, its gravimetric energy density of 18.6 MJ/kg is significantly lower than liquid hydrogen (120 MJ/kg) and methane (55.5 MJ/kg), highlighting a potential drawback in weight efficiency. Despite these limitations, ammonia's ease of storage and handling could offset its lower energy density in specific situations, particularly where infrastructure for hydrogen or methane is limited. The comparison underscores the importance of considering both the volumetric and gravimetric energy densities when selecting fuels for emergency use in space missions.

4.4.2 Challenges of Ammonia Combustion

The use of ammonia as a rocket fuel presents several technical challenges that need to be addressed to optimize its performance. One such challenge is its lower flame speed, ranging between 0.07 and 0.08 m/s, which is considerably slower than methane (0.38 m/s) and hydrogen (2.65 m/s). This slower flame speed can lead to inefficient combustion and pose difficulties in achieving stable burning in rocket engines. Another challenge is the higher ignition energy required for ammonia, which is approximately 8-10 times greater than that of hydrogen. This requirement makes it difficult to initiate combustion, especially in the low-pressure environments typical of space. Additionally, the combustion of ammonia can produce nitrogen oxides (NOx), which are harmful pollutants, necessitating the development of advanced combustion techniques or after-treatment systems to mitigate these emissions, particularly in the confined environments of spacecraft.

4.4.3 Potential of Ammonia-Based Fuel Cells for Space Applications

Ammonia-based fuel cells offer a promising alternative to combustion for utilizing ammonia in space. One approach involves the decomposition of ammonia into nitrogen and hydrogen, with the latter being used in hydrogen fuel cells to generate electricity. This method offers higher energy efficiency compared to direct combustion and is particularly well-suited for space applications where efficient energy use is critical. Solid oxide fuel cells (SOFCs) present another viable option, as they can directly use ammonia to produce electricity with high efficiency. Operating at temperatures between 700°C and 1000°C, SOFCs can convert ammonia into electricity, with water and nitrogen as the only by-products, making them a clean energy source for long-duration missions. The ability to store ammonia in liquid form at moderate pressures further enhances its practicality for space missions. The established industrial infrastructure for ammonia production and handling could simplify logistics and reduce costs, making it an attractive option for future space exploration efforts.

5. The Importance of Research and Development in Rocket Fuel Technologies

In the rapidly evolving field of aerospace, the significance of research and development (R&D) in rocket fuel technologies cannot be overstated. As we look to the stars and beyond, the quest for more efficient, sustainable, and powerful fuel sources becomes increasingly critical. R&D serves as the backbone of innovation, enabling scientists and engineers to explore new methodologies, refine existing processes, and ultimately enhance the performance of rocket propulsion systems.

The landscape of rocket fuel is undergoing a transformation, driven by the need for environmentally friendly alternatives to traditional propellants. As space agencies and private companies alike strive for sustainability, R&D efforts are focused on developing biofuels, green propellants, and hybrid systems that minimize the ecological footprint of space missions. This pursuit not only helps to reduce harmful emissions but also paves the way for the potential reuse of fuel sources, further lowering costs and increasing the viability of long-duration space travel.

Moreover, R&D plays a crucial role in advancing the safety and reliability of rocket fuel technologies. Rigorous testing and experimentation are essential to understanding the behavior of different propellant combinations under various conditions. By delving into the chemical properties and combustion characteristics of new fuel types, researchers can identify and mitigate risks, ensuring that rockets operate safely and efficiently during their missions.

Collaboration across disciplines is another vital aspect of R&D in rocket fuel technologies. Chemists, engineers, and environmental scientists must work together to tackle complex challenges and share insights that drive innovation. This multidisciplinary approach fosters a rich environment for creativity and problem-solving, leading to breakthroughs that could redefine the future of space exploration.

6. Conclusion

As we stand on the brink of a new era in space exploration, the urgency for sustainable fuel solutions has never been more pronounced. The methods discussed throughout this article, from biofuels derived from algae to cutting-edge technologies harnessing solar energy, highlight a pivotal shift in our approach to rocket propulsion. The traditional reliance on fossil fuels not only poses environmental challenges but also threatens the sustainability of our expanding ventures beyond Earth's atmosphere. The path forward must prioritize innovation and collaboration among scientists, engineers, and policymakers. By investing in research and development, we can unlock the potential of alternative fuels that not only reduce our carbon footprint but also enhance the efficiency and safety of space travel. Furthermore, embracing a circular economy model—where waste is minimized, and resources are reused—will play a crucial role in shaping the future of rocket fuels. Education and public awareness are equally vital. As we engage with the next generation of explorers and innovators, we must instill a sense of responsibility towards our planet and its resources. The future of sustainable rocket fuels will depend on our collective commitment to finding solutions that not only push the boundaries of technology but also respect and preserve the environment.

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8. Conflict of Interest

The author declares no competing conflict of interest.

9. Funding

No funding was received to support this study.