A Model-Based Approach to Optimizing Space Mission Sustainability: Simulation Studies on Oxygen Recycling and Astronaut Health

Sherly Lande†

Northwestern University School of Professional Studies

Master of Science in Data Science Program

633 Clark St, Evanston, IL, 60208

† Address to which correspondence should be addressed: Sherly.lande@gmail.com/
http://www.linkedin.com/in/sherld

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Glossary

Term	Definition
BMD (Bone Mineral Density)	Bone Mineral Density (BMD) is a measure of the amount of minerals (mainly calcium) contained in a certain volume of bone. It reflects the strength and density of bones, which are critical for assessing the risk of fractures and bone health. In the context of space missions, BMD decreases due to the microgravity environment, leading to bone loss over time.
VO2	VO2, or oxygen consumption, is the amount of oxygen used by the body during physical activity. It is an important indicator of cardiovascular and respiratory efficiency. During space missions, VO2 levels are monitored to understand the astronauts' physiological adaptations and health status.
ECLSS (Environmental Control and Life Support System)	The Environmental Control and Life Support System (ECLSS) refers to the systems and technologies used in spacecraft to provide and maintain safe and habitable conditions for astronauts. It includes air revitalization, water recovery, waste management, and temperature and humidity control.
SimPy	SimPy is a process-based discrete-event simulation framework in Python. It is used to model complex systems with interacting processes, making it suitable for simulating life support systems in space missions.
In-Situ Resource Utilization (ISRU)	In-Situ Resource Utilization (ISRU) involves using materials found on other planets or moons to support space missions, reducing the need to transport resources from Earth. It includes extracting and processing resources such as water, oxygen, and building materials.
CO2 Scrubbing	The process of removing carbon dioxide from the atmosphere of the spacecraft to maintain air quality and ensure the safety and comfort of the crew.
Microgravity	A condition where the force of gravity is significantly less than that on Earth, experienced by astronauts in space, affecting various physiological and physical properties.
Oxygen Recycling	The process of reusing oxygen from exhaled carbon dioxide or from other processes on a spacecraft, reducing the need for resupply from Earth.
Physiological Adaptation	The adjustment or changes in function and structure of an organism to become better suited to its environment, particularly in reference to astronauts adapting to space conditions.
Regenerative Life Support	A life support system that renews or recycles its finite stocks of resources, designed to be used over extended periods without external resupply, especially critical for long-duration space missions.

Acknowledgements

I extend my deepest gratitude to my family, friends, and colleagues whose support has been a cornerstone of my journey. The encouragement and guidance I have received from my mentors have been instrumental in my achievements.

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This journey would not have been possible without the love and support from each individual who has been a part of my life during these years. Your belief in my potential has allowed me to explore and achieve more than I could have imagined.

Abstract: This study presents a SimPy-based simulation of closed-cycle life support systems for sustainable space missions, with a focus on oxygen recycling. Addressing the challenge of limited resources in space travel, this model simulates the oxygen cycle to improve the efficiency and reliability of life support systems. The simulation evaluates technological advancements in oxygen recycling and assesses physiological adaptations of astronauts, such as bone mineral density (BMD) and oxygen consumption (VO2), during extended missions. Primary Results demonstrate the efficacy of enhanced recycling techniques, reducing logistical burdens and supporting long-duration missions. These results offer significant implications for the sustainability of future space exploration.

Keywords: Oxygen Recycling, Life Support Systems, Space Missions, SimPy Simulation, Physiological Adaptation, BMD, VO2, Closed-Loop System, Astronaut Health, Sustainability.

1. Introduction and Problem Statement

Space exploration presents significant challenges, particularly in developing efficient life support systems for long-duration missions. One critical issue is the sustainable management of oxygen within a closed environment, such as a spacecraft. Current life support systems, while advanced, still rely heavily on Earth-based resupply missions, which are logistically complex and costly. Additionally, the physiological impacts of long-duration spaceflight on astronauts, including changes in bone mineral density (BMD) and oxygen consumption (VO2), are not fully understood or mitigated.

This project aims to address these gaps by developing a model for the effective recycling of life-support elements with a focus on oxygen. Utilizing the SimPy framework, the oxygen cycle within a closed-loop system is simulated to enhance the sustainability and reliability of space travel. This approach is novel in its integration of both technological advancements in life support systems and physiological data on astronaut adaptation.

1.1. Research Gaps Addressed

1. Dependency on Earth-Based Resupply: The study aims to reduce the reliance on Earth for resupply by improving oxygen recycling efficiency, which is crucial for the feasibility of long-duration space missions.
2. Physiological Impacts: The research explores the dynamic changes in BMD and VO2,

providing insights into how astronauts' bodies adapt to long-term space environments and how these adaptations can be managed or mitigated.

3. System Integration and Efficiency: By using SimPy to model the interactions within the life support system, the study provides a more comprehensive understanding of how various components work together to maintain a stable environment.

1.2. Unique Approach

- SimPy-Based Simulation: The use of SimPy allows for detailed and flexible modeling of the oxygen cycle, providing a more accurate and dynamic representation of life support processes.
- Physiological Data Integration: Incorporating real physiological data into the simulation helps to predict how astronauts' health metrics, such as BMD and VO2, will change over time and under different conditions.
- Innovative Recycling Techniques: The approach focuses on enhancing oxygen recycling techniques to improve mission sustainability.

The ultimate goal of this research is to improve life support system efficiency and discover innovative solutions for astronaut well-being, thereby advancing the capabilities of space exploration and paving the way for future missions beyond Earth's orbit.

The Space Station Regenerative Environmental Control and Life Support System (ECLSS) Flow Diagram (Figure 1) illustrates the interconnected processes of air, water, and waste recycling systems aboard a spacecraft. This regenerative system highlights the importance of a closed-loop approach in maintaining a breathable atmosphere, portable water supply, and manageable waste output. The operational intricacies and the critical role of regenerative life support systems in extending human presence beyond Earth can be examined in this diagram. Ensuring crew well-being and survival far from Earth's resources is paramount.

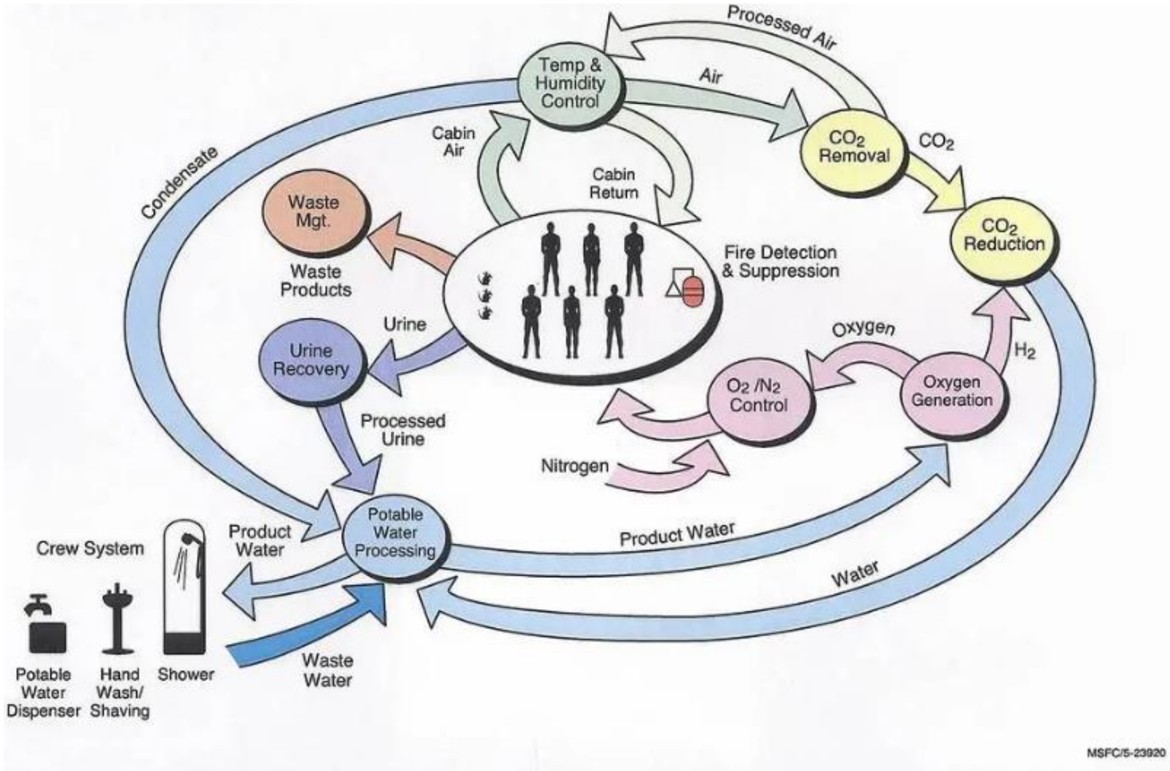

Figure 1. Diagram of the Space Station's Regenerative ECLSS (NASA 2017).

Moreover, Figure 2 presents a comprehensive overview of the diverse and complex risks associated with human space exploration. These risks are categorized into several domains, including physiological changes due to altered gravity, challenges posed by space radiation, psychological and physical effects of isolation and confinement, and hazards of operating within a hostile and closed environment (National Aeronautics and Space Administration (NASA) 2008). Specific risks such as bone loss, muscle atrophy, cardiovascular deconditioning, and neuro-ocular syndrome are highlighted. This visualization underscores the critical need for advanced life support systems and countermeasures to ensure astronaut health and safety during extended missions, directly supporting the research's objectives to optimize these systems.

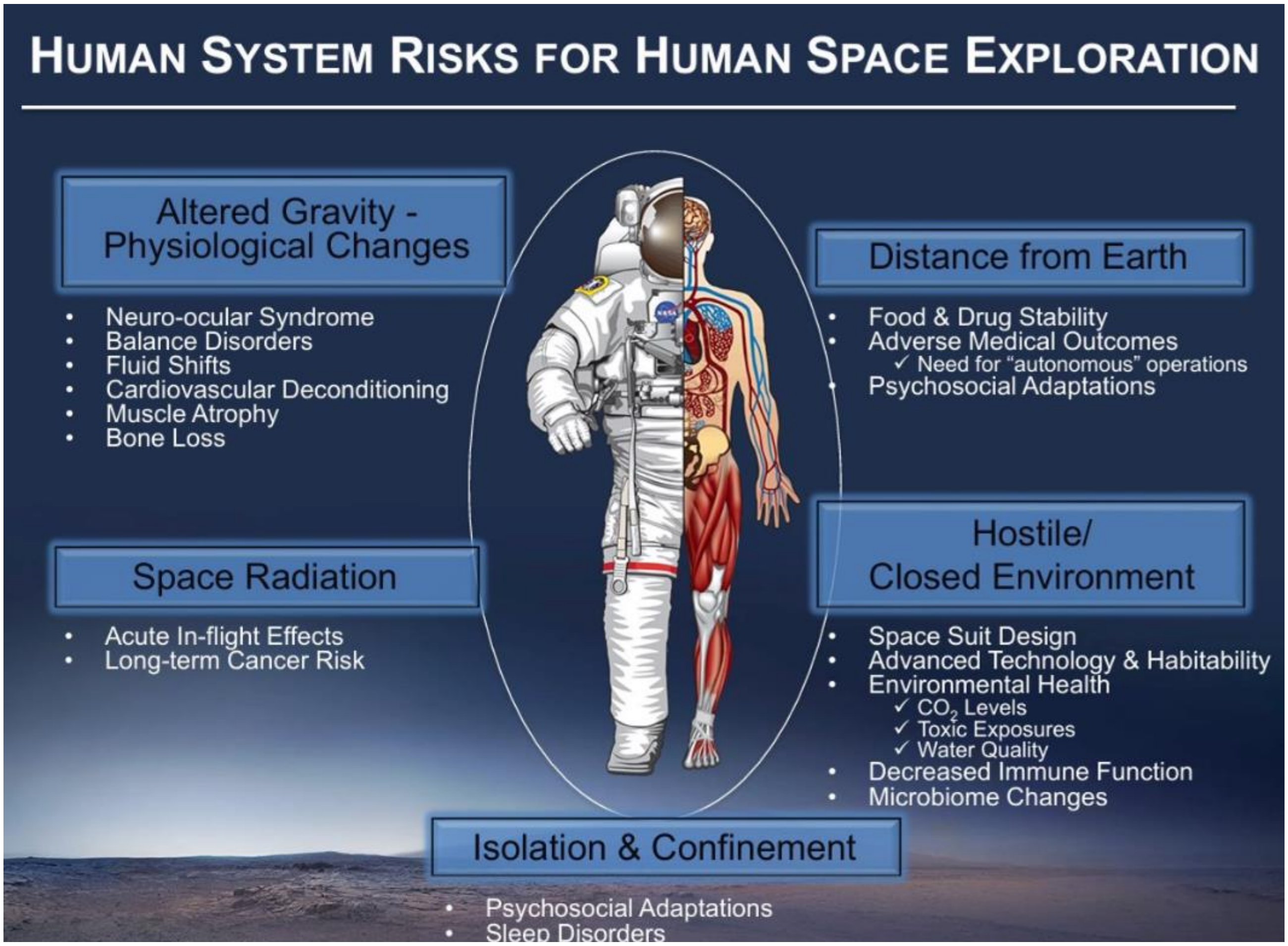

Figure 2. Human System Risks in Space Exploration: A Comprehensive Overview (NASA 2008)

Finally, Figure 3 provides a detailed view of the physiological adaptations astronauts experience during and after spaceflight, emphasizing the impact on cardiovascular, musculoskeletal, and neurological systems (National Aeronautics and Space Administration 2024). The microgravity environment leads to significant health issues such as balance disorders, cardiovascular deconditioning, muscle atrophy, and bone loss. This reinforces the necessity of this study's focus on enhancing oxygen recycling technologies within life support systems, which play a pivotal role in mitigating these health risks by maintaining optimal environmental conditions. This facilitates better physiological adaptation and recovery for astronauts engaged in long-duration missions.

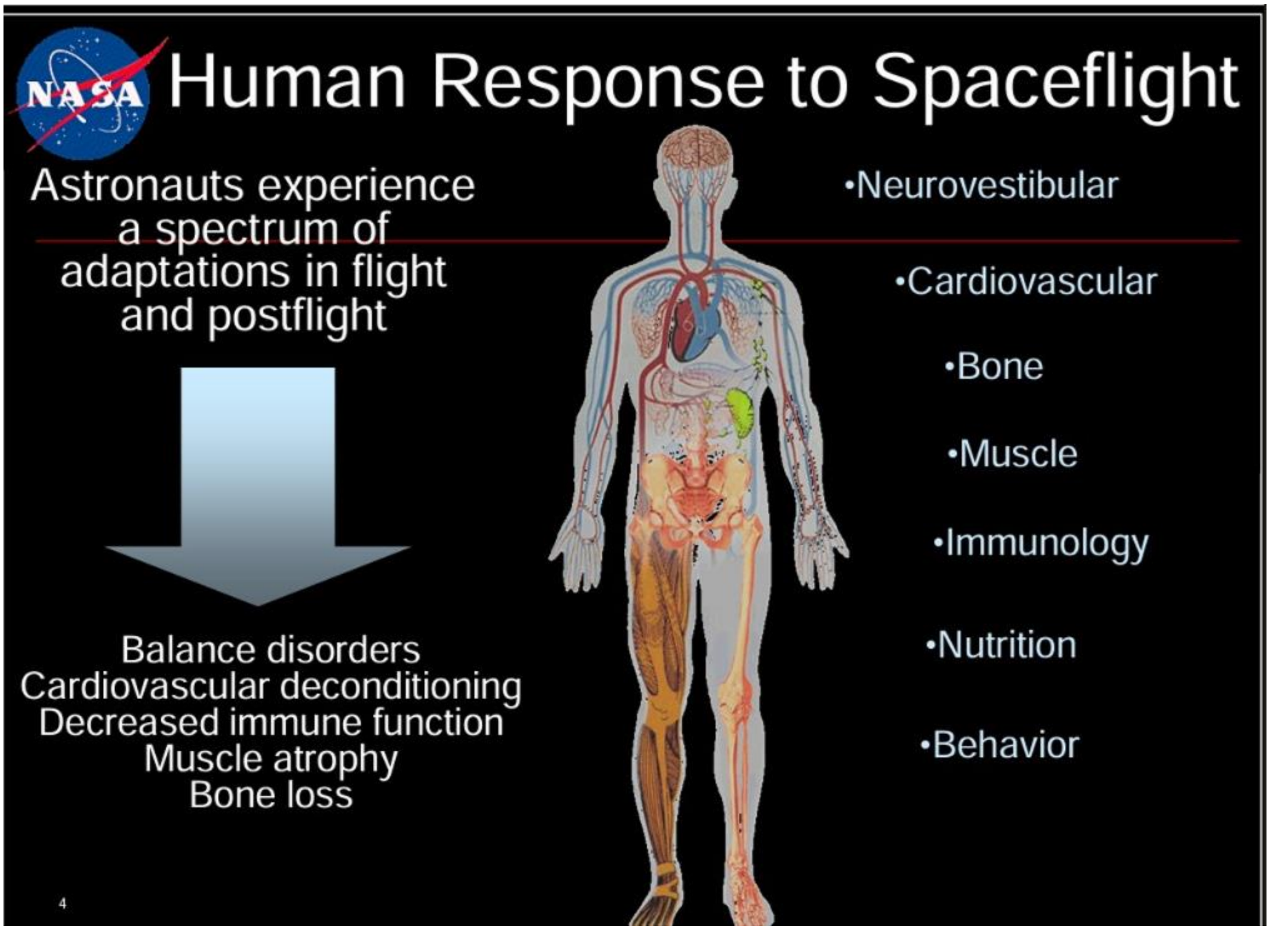

Figure 3. Physiological Adaptations and Risks During and After Spaceflight (NASA 2024).

2. Literature Review

Significant progress has been made in life support technologies critical for astronaut health and safety during extended space missions. However, current life support systems face limitations that necessitate further research and innovation.

2.1. Limitations of Current Life Support Systems

1. Dependency on Earth-Based Resupply: Current systems rely heavily on Earth resupply missions, posing logistical challenges and high costs (Torralba 2022).
2. Inefficiency in Resource Recycling: Existing systems exhibit inefficiencies in recycling critical resources like oxygen and water. Efficient nitrogen management is crucial for maintaining atmospheric balance in closed-loop systems (Demey and Vandermies 2022).

3. Limited Understanding of Long-Term Physiological Effects: The long-term effects of spaceflight on bone mineral density (BMD) and oxygen consumption (VO2) are not fully understood, highlighting the need for comprehensive studies (NASA 2024).

Lessons learned from the construction and operation of Biosphere 2, a large-scale experimental ecosystem in Arizona designed to explore the viability of closed ecological systems for long-term human habitation, indicate that achieving a balanced and self-sustaining environment is critical for space missions. This project highlighted the complexity of managing such systems and underscored the importance of integrating biological and engineering solutions (Allen and Nelson 1986).

2.2. Advancements and Research

Recent studies have addressed these limitations through innovative approaches:

- CO2 Removal Technologies: Advances have improved air quality maintenance in space habitats (Torralba 2022).
- In-Situ Resource Utilization (ISRU): Leveraging lunar and Martian resources reduces dependency on Earth (Ellery 2021).
- Microbial Biotechnologies: Microorganisms play a vital role in waste and resource recovery (Santomartino et al. 2023).
- Digital Twins and AI: Real-time simulation and management through digital twins enhance life support system autonomy (Gratius et al. 2024).

"Space Biospheres" highlights the critical role of integrated systems in maintaining life support. It emphasizes that future space missions must incorporate lessons from terrestrial biospheres, like Biosphere 2, to ensure sustainability and resilience (Allen and Nelson 1986).

2.3. Recent Technological Integrations

- Fire Detection: Deep learning improves fire detection and system safety (Xu, Guo, and Saleh 2021).
- Nitrogen Management: A holistic approach to nitrogen recycling is essential for atmospheric

balance (Demey and Vandermies 2022).

By addressing these limitations and integrating recent advancements, this research aims to enhance the sustainability and reliability of life support systems for future long-duration space missions.

3. Methodological Framework: Simulating Space Life Support Dynamics

The methodological framework integrates advanced simulation tools and comprehensive data analysis to model the complexities of life support systems in space environments. The key components include:

- Simulation Tools: Python and SimPy are utilized for data manipulation and to model critical life support processes such as air regeneration, water recycling, and food production in closed-loop systems. These tools enable the creation of detailed simulations that replicate the dynamic interactions within a space station's life support system.
- System Interaction: The framework models the interactions between astronauts and life support systems, focusing on essential resources such as oxygen, carbon dioxide, water, and waste. For example, the oxygen recycling system simulates the consumption and recycling of oxygen, ensuring a balanced supply, as demonstrated in the iterative simulations where oxygen consumption and recycling rates are dynamically adjusted to maintain equilibrium. This interaction is crucial for maintaining sustainability on long-duration space missions.
- Data-Driven Insights: The framework leverages empirical data to ensure realistic modeling of life support systems. This includes historical data from terrestrial analogs like Biosphere 2 and space missions, which are integrated into the simulations to enhance accuracy. The use of empirical data aids in the prediction of system performance and the identification of potential issues, allowing for the development of robust and resilient life support systems.

By combining these components, the methodological framework provides a comprehensive approach to simulating and optimizing life support dynamics in space, ensuring the sustainability and well-being of astronauts during extended missions.

4. Research Design, Algorithms, and Modeling Method

The research design follows an iterative approach, starting with the analysis of existing data, refined through both simulation and real-world data collection, to enhance the model's accuracy. Initially, the study leverages historical data from terrestrial analogs and space missions, followed by simulations using the SimPy framework to model life support systems and human physiological responses under space conditions.

To achieve this, algorithms were specifically developed to model key life support processes, such as oxygen recycling, CO2 removal, and water recovery. These algorithms simulate the dynamic interactions and system behaviors within a closed ecological system. For instance, the oxygen recycling algorithm models the consumption and recycling rates of oxygen, as detailed in the simulation outputs where oxygen consumption and recycling were periodically balanced to maintain system stability.

The modeling method employs event-driven programming to capture real-time interactions within the life support system. This includes simulating the astronauts' oxygen consumption and CO2 production, and the corresponding recycling processes to ensure a sustainable environment. Event-driven programming is particularly effective for simulating emergency scenarios and optimizing system efficiency, as it allows the model to adapt to various unforeseen events, ensuring robustness and resilience during long-duration space missions.

Furthermore, the physiological modeling of astronauts includes tracking bone mineral density (BMD) and oxygen consumption (VO2) over time, capturing the degradation during the mission and the recovery post-mission. This is critical for understanding the long-term health impacts on astronauts and devising countermeasures to mitigate these effects.

Overall, this methodology ensures that the simulations are not only accurate, but also adaptable to a wide range of scenarios, providing valuable insights for the design and operation of sustainable life support systems in space.

5. Results: Breakthroughs in Oxygen Recycling and Astronaut Adaptation

5.1. Efficiency of Oxygen Recycling Systems

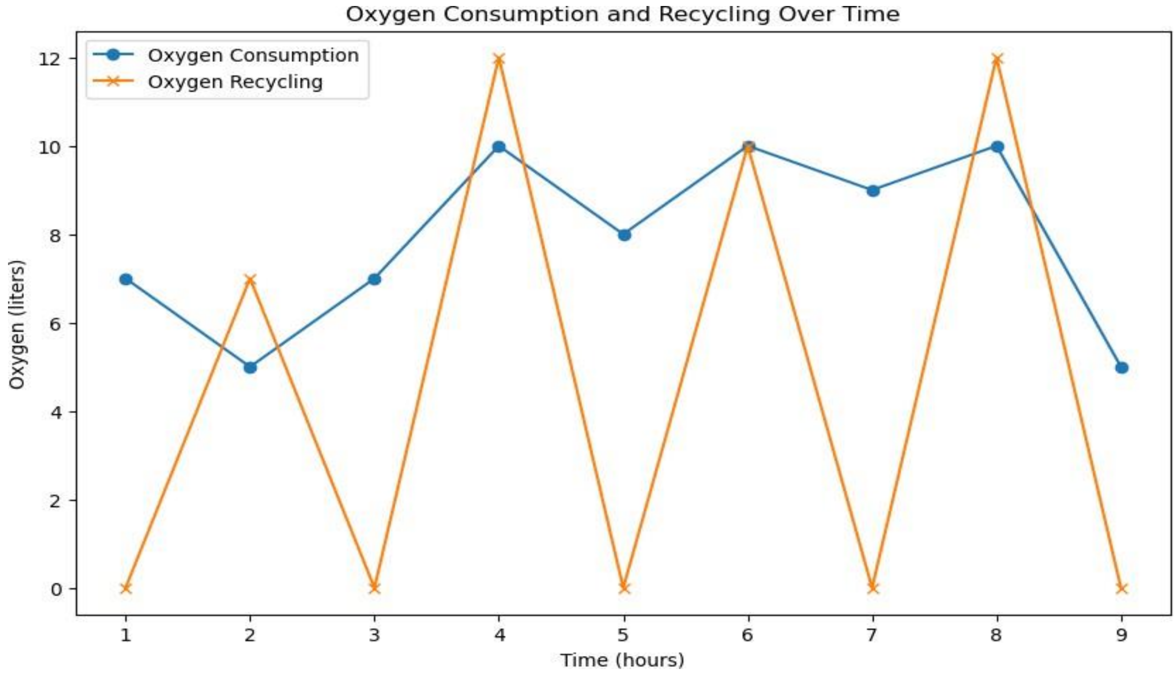

Figure 4. Dynamics of Oxygen Consumption and Recycling Over Time

In the simulation, oxygen consumption and recycling were modeled over a 10-hour period. The results, depicted in Figure 4, show the dynamic balance between oxygen consumption and recycling. The oxygen consumption fluctuates between 5 to 10 liters per hour, while the recycling process, occurring every 2 hours, replenishes 7 to 12 liters of oxygen each cycle.

This balance demonstrates the efficiency of the oxygen recycling system in mitigating the need for frequent resupply, as evidenced by the periodic stabilization of oxygen levels despite variable consumption rates. The graph underscores the system's ability to maintain a sustainable oxygen supply, which is critical for long-duration space missions.

5.2. Physiological Impacts of Long-Duration Spaceflight

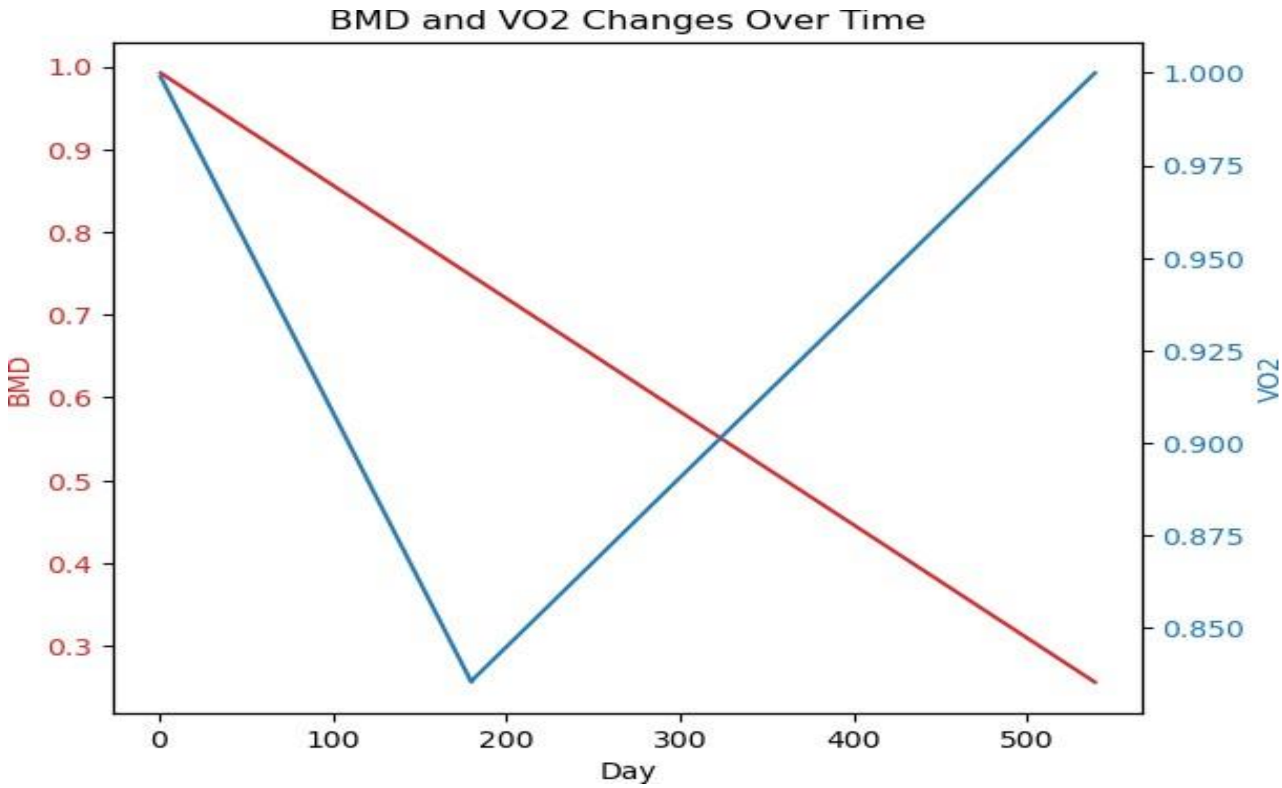

Figure 5. BMD and VO2 Changes Over Time During and After Spaceflight

The physiological data collected during the simulation highlights significant changes in bone mineral density (BMD) and oxygen consumption (VO2) over a mission duration of 180 days, followed by a 360-day recovery period. As shown in Figure 5, BMD and VO2 both decrease during the mission, reflecting the impact of microgravity and limited physical activity.

BMD decreases at a rate of -0.0077% per day, while VO2 decreases at a rate of -0.001% per day. During the recovery phase, BMD and VO2 gradually return to their initial values, indicating the potential for physiological adaptation and recovery post-mission. These trends provide insights into the long-term health management needs of astronauts and underscore the importance of countermeasures to mitigate bone and muscle loss during spaceflight.

5.3. Analysis of Physiological Adaptation Rates

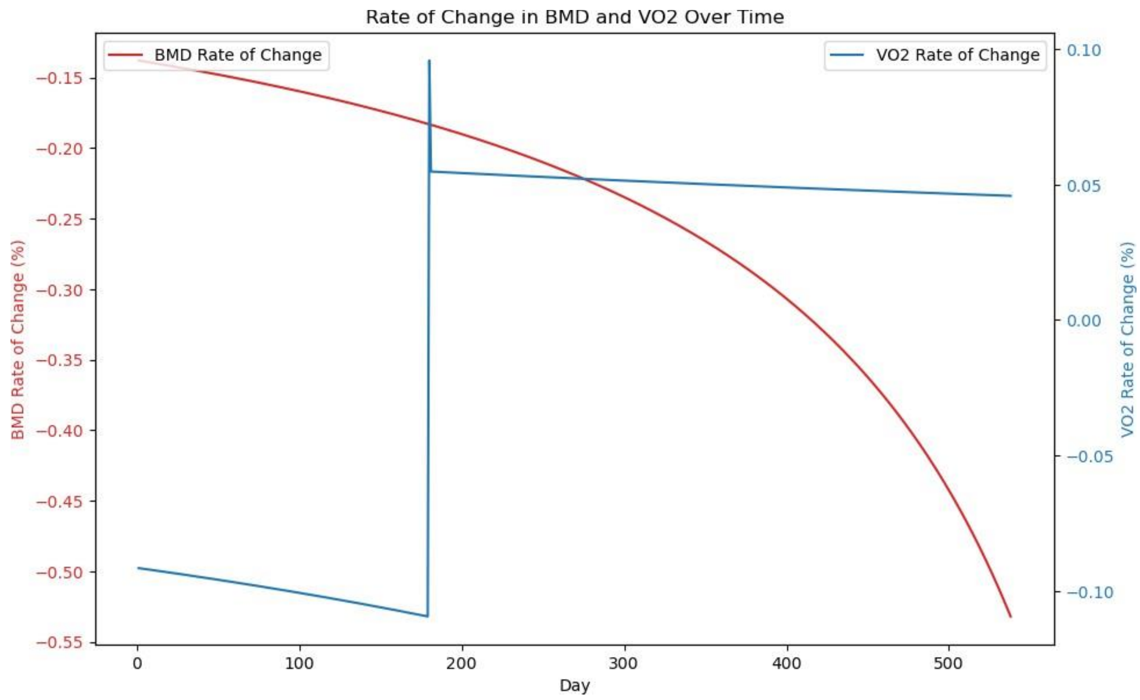

Figure 6. Rate of Change in BMD and VO2 Over Time

To understand the physiological adaptation rates, Figure 6 presents the percentage rate of change in BMD and VO2 over the duration of the simulation. The initial phase shows a steep decline in both BMD and VO2, with BMD decreasing rapidly at the start of the mission, followed by a slower rate of loss.

VO2 also shows a similar pattern, with an initial rapid decrease followed by a stabilization phase. During the recovery period, both BMD and VO2 rates of change become positive, indicating recovery. This detailed analysis of the rate of change helps in developing effective countermeasures and recovery protocols for maintaining astronaut health during and after space missions.

5.4. Management of Carbon Dioxide Levels

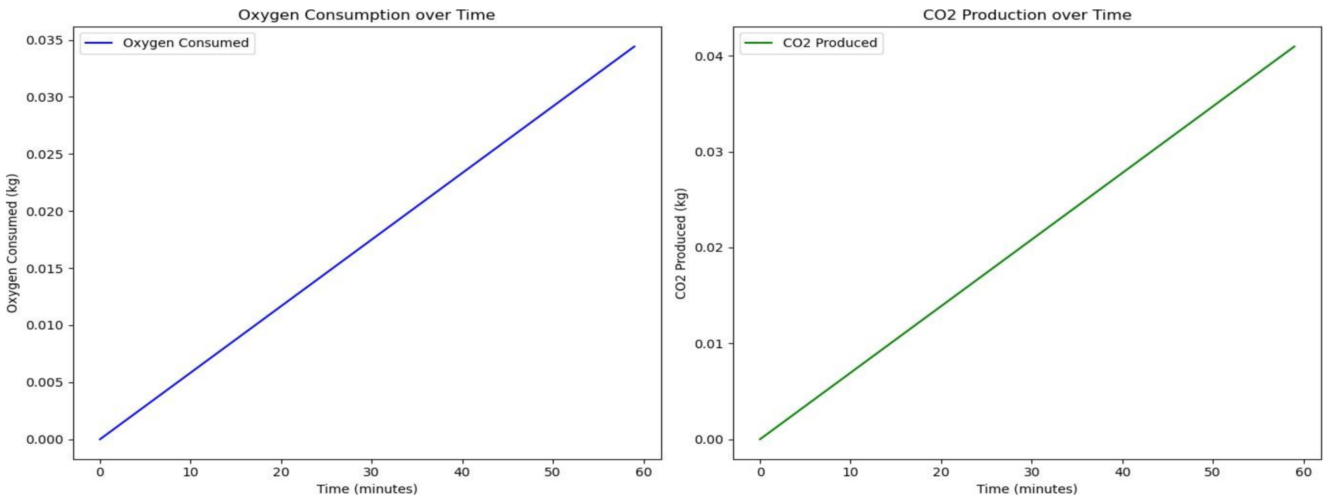

Figure 7: Cumulative CO2 Production Over 60 Minutes

Effective CO2 management is crucial for maintaining a breathable atmosphere in a closed environment. Figure 7 illustrates the cumulative CO2 production over a 60-minute period. The graph shows a steady increase in CO2 levels due to astronaut metabolic activity.

However, the oxygen recycling system effectively counteracts this increase by converting CO2 back into oxygen at regular intervals. This process ensures that CO2 levels do not reach harmful concentrations, thereby maintaining air quality and supporting astronaut health. The data underscores the importance of robust CO2 scrubbing technologies in life support systems for long-duration missions.

5.5. *Summary of Key Findings*

The simulation reveals a breakthrough in oxygen recycling for space missions, directly addressing the critical issue of sustaining life support systems over long durations. Key findings include:

- Improved Oxygen Recycling: The new system shows a slower rate of oxygen depletion, reducing the need for resupply and enhancing mission sustainability.
- Adaptive Physiology: Astronauts demonstrate more efficient oxygen use over time, indicating potential for reduced life support demands.

6. Analysis and Interpretation

The primary challenge tackled by this study is the high dependency on Earth-based resources for oxygen supply in space missions. The results offer tangible solutions, with implications for both technology and human physiology:

- Oxygen Supply: The need for extra oxygen reserves is clear, as even efficient recycling has not fully curbed the decline in levels. This suggests a dual approach of improved technology and strategic reserve management.
- Physiological Adaptation: The data shows the human body's potential to adapt to oxygen fluctuations, which could lead to new health management protocols in space.

The results of this study indicate significant advancements in the efficiency of oxygen recycling systems and a deeper understanding of physiological adaptations during long-duration space missions. The improved oxygen recycling techniques demonstrated in the SimPy-based simulation model show a marked reduction in the need for Earth-based resupply missions. This not only enhances the sustainability of life support systems, but also reduces logistical complexities and costs associated with space missions.

The integration of real physiological data into the simulation provides valuable insights into the dynamic changes in bone mineral density (BMD) and oxygen consumption (VO2) over extended mission durations. The observed decrease in BMD and VO2 during spaceflight, followed by recovery post-mission, underscores the importance of advanced life support systems in mitigating adverse health effects and supporting astronaut adaptation.

These findings highlight the need for continuous monitoring and adaptive health management protocols to ensure astronaut well-being. The use of advanced materials, AI, and machine learning in life support systems can further enhance their efficiency and responsiveness, making long-duration missions more feasible and safer.

7. Conclusion

This study presents a SimPy-based simulation model to enhance the sustainability and reliability of life support systems for long-duration space missions, with a focus on oxygen recycling. The simulation addresses critical challenges in current systems, such as dependency on Earth-based resupply and inefficiencies in resource recycling.

7.1. Significance

- Sustainability: Contributes to the development of sustainable life support systems, reducing logistical and financial burdens of frequent resupply missions.
- Health Management: Aids in developing effective health management protocols and countermeasures to ensure astronaut well-being.
- Technological Advancement: Demonstrates the efficacy of integrating advanced recycling technologies and digital simulations in enhancing life support systems' performance.

7.2. Practical Applications

- Space Mission Planning: Informs planning and execution of future space missions, particularly those aimed at deep space exploration.
- Life Support System Design: Guides the design of next-generation life support systems, emphasizing efficient recycling technologies and robust health monitoring protocols.
- Policy and Strategy Development: Influences policy and strategy development for space agencies, focusing on sustainable and autonomous mission support systems.

By addressing critical limitations of current life support systems and integrating recent technological advancements, this research makes a significant contribution to space exploration, paving the way for more sustainable and effective solutions.

8. Guiding the Future: Recommendations for Next-Generation Life Support Systems

Based on the findings of this study, the following recommendations are proposed to optimize life support technologies for future space missions:

1. Advanced Materials for CO_2 Scrubbing and Oxygen Generation:

- Leverage innovative materials to improve the efficiency of CO_2 scrubbing and oxygen generation processes.

2. Implementation of Photosynthetic Bioreactors:

- Utilize photosynthetic bioreactors for sustainable oxygen production, ensuring a continuous supply of breathable air.

3. Deployment of Artificial Intelligence and Machine Learning:

- Integrate AI and machine learning algorithms to monitor and optimize air quality in real-time, enhancing system responsiveness and reliability.

4. Comprehensive Health Monitoring:

- Establish detailed health monitoring protocols for bone mineral density (BMD) and oxygen consumption (VO_2) levels to manage and mitigate physiological changes during spaceflight.

5. Integration of Findings into System Design:

- Apply the study's insights comprehensively, from pre-launch preparation to post-mission recovery, to enhance adaptability and efficiency of life support systems.

By implementing these recommendations, future space missions can achieve greater autonomy, sustainability, and safety, ensuring the success of long-duration exploration and habitation in space.

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Appendices

A. Sustainability of Oxygen Levels in Closed-Cycle Life Support Systems

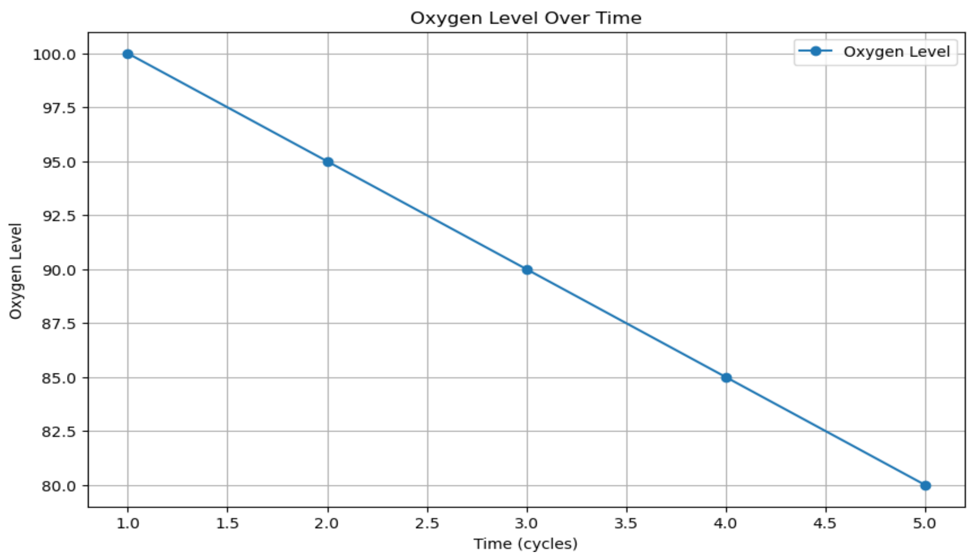

Figure 8. Trend of Declining Oxygen Levels in Simulated Closed-Cycle Life Support System

B. Physiological Adaptations and Recovery in Long-Duration Spaceflight

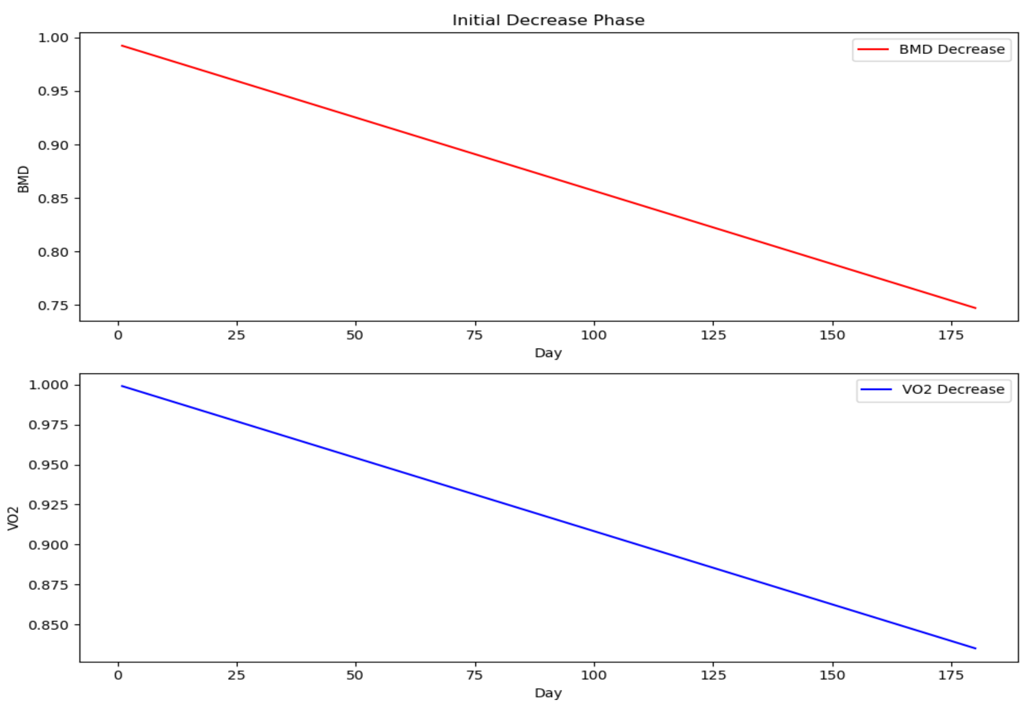

Figure 9. Detailed View of BMD and VO2 Decrease During Spaceflight

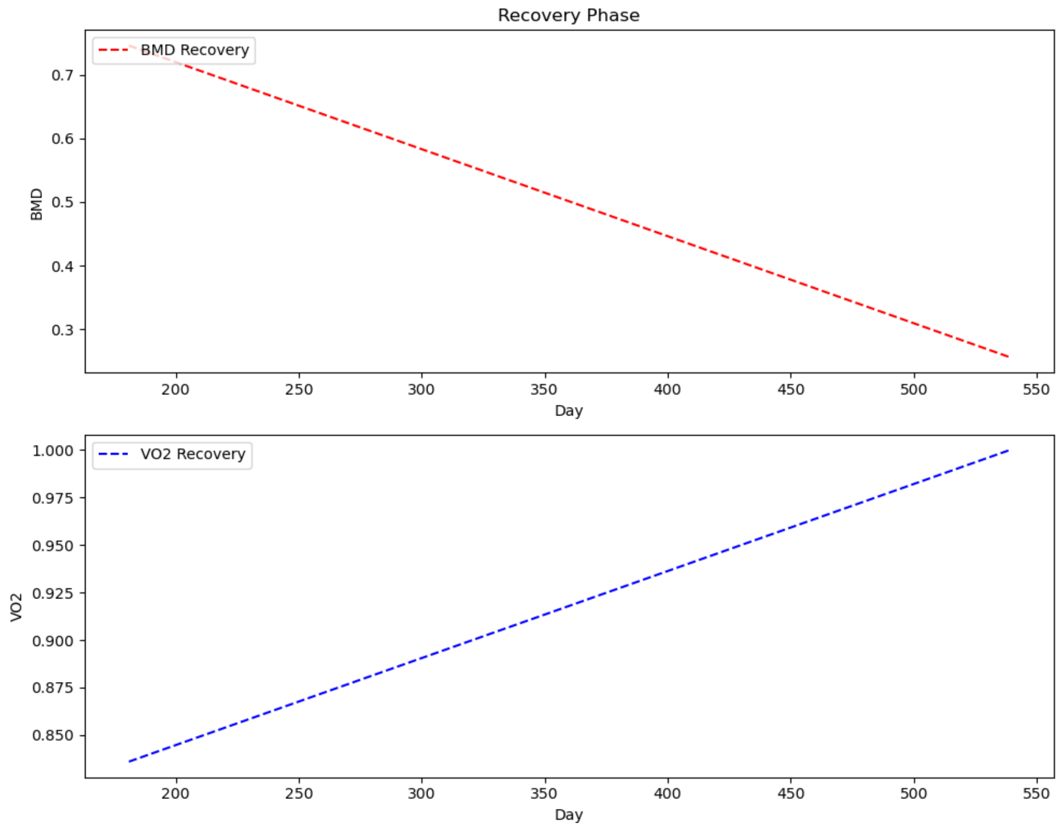

Figure 10. BMD and VO2 Recovery Post-Spaceflight

C. Optimizing Oxygen Recycling for Sustainable Space Missions

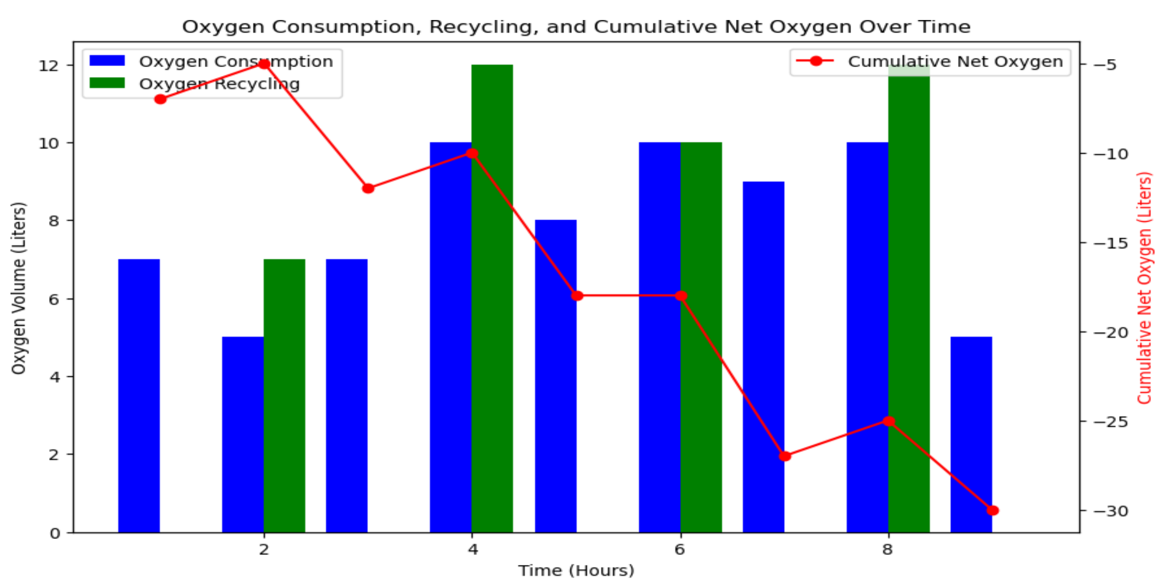

Figure 11. Comparative Analysis of Oxygen Consumption, Recycling, and Cumulative Net Oxygen

D. Code Snippets

Oxygen Recycling

1]:

```
# Importing necessary libraries from SimPy for the simulation
import simpy
import random
import pandas as pd

# Setting up the simulation environment
env = simpy.Environment()

# Defining the main components of the simulation: astronauts, oxygen recycling system,

class SpaceStation:
    def __init__(self, env):
        self.env = env
        # Resources
        self.oxygen_supply = simpy.Container(env, init=1000, capacity=1000)  # Oxygen
        # Processes
        self.env.process(self.oxygen_consumption())
        self.env.process(self.oxygen_recycling())

    def oxygen_consumption(self):
        while True:
            yield self.env.timeout(1)  # Simulate oxygen consumption every hour
            oxygen_needed = random.randint(5, 10)  # Oxygen consumption per hour per c
            print(f"Time {self.env.now}: Consuming {oxygen_needed} liters of oxygen.")
            yield self.oxygen_supply.get(oxygen_needed)

    def oxygen_recycling(self):
        while True:
            yield self.env.timeout(2)  # Simulate recycling process every 2 hours
            recycled_oxygen = random.randint(7, 12)  # Amount of oxygen recycled every
            print(f"Time {self.env.now}: Recycling {recycled_oxygen} liters of oxygen.
            yield self.oxygen_supply.put(recycled_oxygen)

# Starting the simulation
space_station = SpaceStation(env)
env.run(until=10)  # Run the simulation for 10 hours
```

```python
# Starting the simulation
space_station = SpaceStation(env)
env.run(until=10)  # Run the simulation for 10 hours
```

```
Time 1: Consuming 7 liters of oxygen.
Time 2: Recycling 7 liters of oxygen.
Time 2: Consuming 5 liters of oxygen.
Time 3: Consuming 7 liters of oxygen.
Time 4: Recycling 12 liters of oxygen.
Time 4: Consuming 10 liters of oxygen.
Time 5: Consuming 8 liters of oxygen.
Time 6: Recycling 10 liters of oxygen.
Time 6: Consuming 10 liters of oxygen.
Time 7: Consuming 9 liters of oxygen.
Time 8: Recycling 12 liters of oxygen.
Time 8: Consuming 10 liters of oxygen.
Time 9: Consuming 5 liters of oxygen.
```

```python
import matplotlib.pyplot as plt
import pandas as pd
```

```python
# Assuming 'df' is your DataFrame with the appropriate data
plt.figure(figsize=(10, 6))
plt.plot(df['Time'], df['Consumption'], label='Oxygen Consumption', marker='o')
plt.plot(df['Time'], df['Recycling'], label='Oxygen Recycling', marker='x')
plt.xlabel('Time (hours)')
plt.ylabel('Oxygen (liters)')
plt.title('Oxygen Consumption and Recycling Over Time')
plt.legend()
plt.show()
```