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Original Article

Nutrition optimization in space stations under microgravity: A mathematical model and solution approach

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ABSTRACT

This study presents a comprehensive mathematical model to optimize astronaut nutrition under microgravity conditions, addressing critical health challenges during lengthy space missions. The proposed model integrates advanced statistical techniques, such as the Design of Experiments (DOE) and Analysis of Variance (ANOVA), to optimize dietary strategies for preventing muscle atrophy, preserving bone density, and maintaining metabolic balance. The model's key innovation lies in its ability to accurately predict the nutritional needs of astronauts by optimizing the intake of essential nutrients, such as proteins, vitamins, and minerals, based on empirical data and National Aeronautics and Space Administration's (NASA's) dietary guidelines. The findings indicate significant improvements in nutritional outcomes over existing methods, as the model generates tailored dietary plans that dynamically adapt to the unique physiological changes induced by microgravity. These improvements are validated through cross-validation techniques and through sensitivity analysis, confirming the model's reliability and applicability in space environments. This research establishes a new standard in astronaut nutrition through a systematic, data-driven approach adaptable for future space missions. It underscores the necessity of personalized nutrition strategies to enhance astronaut health and performance, contributing to mission success and sustainability. The study's innovative methodology also paves the way for future research, exploring more refined optimization techniques and broader applications across diverse astronaut profiles.

1. Introduction

Space remains one of humanity's greatest frontiers and continues to be a fascinating environment with unexplored boundaries. Space missions are exciting journeys that inspire people to solve the mysteries of the world outside and step outside our planet. However, living in space is fraught with unique challenges and risks, one of the most important of which is the lack of gravity. The lack of gravity is a factor that greatly affects the daily life and health of astronauts. Especially in long-term missions, it is extremely important for astronauts to eat healthy, prevent muscle loss, and maintain energy levels. The nutritional needs of astronauts in space differ from traditional nutritional approaches. This difference is due to the unique challenges created by the microgravity environment (Takahashi et al., 2017). The development of mathematical models and nutritional strategies is critical to ensure that astronauts are adequately and healthily nourished in long-term space missions. Additionally, this literature review will benefit from the findings of the previous research on nutrition optimization in space stations to contextualize this study better.

When reviewing the literature, it is seen that the challenges faced in nutrition in space and solutions to these challenges are emphasized. The physiological effects of space missions reveal the critical impact of nutrition on the health of astronauts. These studies highlight the importance of astronauts eating healthy on space missions, showing that nutrition optimization is a critical component for the success of space missions. Hackney and colleagues (2015) found that long-term exposure to conditions in space leads to a loss of conditioning in the neuromuscular and cardiovascular systems, resulting in a decrease in physical fitness. They emphasized that this loss of conditioning could negatively affect physical performance in gravitational environments, and therefore, various approaches such as nutritional supplements and drugs that can help reduce physiological conditioning loss in long-term space journeys should be investigated. Oluwafemi and colleagues (2018) addressed the nutritional and food needs of long-term human space missions. While food can be stockpiled for short-term missions, they explored alternatives, such as nutrition and plant cultivation, for long-term missions. This study addresses possible solutions for plant cultivation and astronaut nutrition for long-term missions to different celestial bodies in space (Moon, Mars, Venus). The research focuses on how plants can be grown on these celestial bodies, what methods can be used, and how they can meet the nutritional needs of astronauts. Di Girolamo et al. (2020) conducted the NutrISS Study, a proof-of-concept research sponsored by the European Space Agency (ESA) and executed on the International Space Station (ISS) from July 2019 to January 2020. This study focused on monitoring the body composition of astronauts during long-term spaceflight to provide nutritional advice as needed. The study utilized a Bio-Impedance Analyser (BIA) for assessing body composition and aimed to maintain astronauts in near-neutral energy balance, offering advice on energy intake when necessary. This approach effectively counters the detrimental effects

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of microgravity on skeletal muscle mass and metabolism. Bychkov and colleagues (2021) conducted a significant study that examined the current state and future trends of nutrition in space by addressing the nutritional needs of astronauts in space. Their research focuses on the history of astronaut nutrition and highlights the effects of nutrition based on current knowledge of the physiological processes of space missions. Their findings suggest that a balanced diet can reduce the potential risks faced by astronauts in space missions and that the development of the space nutrition industry can protect the health of astronauts. Smith and Zwart (2021), in their article "Nutrition as Fuel for Human Spaceflight," emphasize the crucial role of nutrition in human space exploration. They review the impact of nutrition during spaceflight in the era of the International Space Station (ISS) and highlight key areas where further research is needed. The study discusses how nutrition can significantly influence astronaut health and performance, noting that failing to optimize nutrition could jeopardize mission success. Additionally, they explore the challenges of nutrition in space, considering operational and vehicle constraints, especially for missions beyond the low Earth orbit. Kumar and his team (2022) emphasized the importance of understanding the nutritional needs of humans in space. They stated that nutritional requirements become complex due to physiological changes and that malnutrition can lead to muscle and performance loss while overeating can lead to heart disease, obesity, and other health problems. Therefore, they emphasize the need to closely monitor the nutritional needs of astronauts during space missions and to make appropriate nutritional arrangements. Chaloulakou et al. (2022) analyze the pathophysiological changes in astronauts due to various space environment stressors like microgravity, space radiation, and confinement. They emphasize the critical role of nutrition in mitigating these effects, including bone and muscle mass loss. The study also discusses the historical inadequacy of space food in fully meeting astronaut nutritional needs, leading to issues like menu fatigue and unintentional weight loss. This comprehensive review explores nutrition's role in addressing the physiological challenges faced by astronauts during spaceflight. Tang et al. (2022) have conducted research on maintaining optimal nutritional intake during extended stays on Mars or the Moon, focusing on new food forms and food allocation strategies for deep-space manned missions. This study provides significant insights into the formulation and processing of functional foods required for astronauts on lengthy missions. It aims to expand the current knowledge and optimize nutrition strategies for future space missions, addressing the critical need for sustainable and efficient nutrition in space exploration contexts. Kumar and Gaikwad (2023) examined the evolution of food packaging systems in space research missions. They highlighted advancements in food processing, preservation, and packaging technologies for space exploration. The research categorized various types of space foods and analyzed the packaging materials and forms used. The study underscored challenges in space food packaging, focusing on efforts by agencies such as NASA, JAXA, and DRDO to improve food quality and nutrition for crew members. The role of packaging in ensuring food safety, nutrition, and crew acceptability was emphasized. Shu provided a mathematical optimization approach for selecting nutrient-dense space crop combinations, highlighting the importance of circular economy and water efficiency metrics for long-term missions. Mathur reviewed recent innovations like silkworm protein and 3D food printing, underscoring their relevance to microgravity conditions. Pittia et al. (2023) explored nutrient bioavailability and energy-dense diets as critical factors for maintaining astronauts' health during extended missions. Banerjee (2022) examined food processing classifications and pre-planned menus for different international space programs, emphasizing the engineering aspects of space food systems. Finally, Douglas et al. (2022) demonstrated the positive impact of flavonoid- and omega-3-rich diets on astronauts' cognitive and physical health, further supporting the need for enhanced dietary strategies. Pandith et al. (2023) conducted a comprehensive review of the advancements in space food suitable for microgravity environments. Their study discusses the evolution of space food from the 1960s through to the projected needs of the 2030s, emphasizing the development of nutrient-dense and long-lasting food options for astronauts. They address the unique challenges of creating food that remains stable in a microgravity environment and delve into innovative solutions such as 3D printing and space farming. This research is crucial in highlighting the significance of these advancements for ensuring astronaut health and meeting the nutritional demands of extended space missions.

In the extant literature, research focuses on addressing the challenges and solutions related to astronaut nutrition in space, particularly under the unique constraints of the microgravity environment. These studies, summarized in Table 1, explore various aspects such as nutrient density, shelf life, and stability of food, along with innovative solutions like 3D printing and space farming. They collectively underscore the importance of nutritional optimization for astronaut health and performance. However, this study, introduces a distinct approach with its innovative mathematical model, designed to optimize astronaut nutrition on space stations. This model, employing sophisticated statistical methodologies including DOE and ANOVA, addresses comprehensive nutritional requirements while considering the specific conditions of space habitation. The approach outlined in this study

Table 1.
Summary of key studies on astronaut nutrition in space.

Author(s)	Year	Study focus	Methodology	Key findings	Unique contribution
Hackney et al.	2015	Effects of space travel on neuromuscular and cardiovascular systems	Empirical research	Long-term space travel leads to a loss of conditioning in these systems.	Suggested investigation into nutritional supplements and drugs to reduce physiological conditioning loss.
Oluwafemi et al.	2018	Nutritional and food needs for long-term space missions	Exploratory research	Explored alternatives such as plant cultivation for long-term missions.	Proposed solutions for plant cultivation and astronaut nutrition on different celestial bodies.
Di Girolamo et al.	2020	Monitoring body composition in space (NutrISS Study)	Bio-Impedance Analysis (BIA)	Effective maintenance of body composition and energy balance.	Utilized BIA for real-time nutritional advice in microgravity.
Smith & Zwart	2021	Role of nutrition in human space exploration	Review and analysis	Nutrition significantly influences astronaut health and performance.	Discussed challenges and the need for further research in space nutrition.
Kumar et al.	2022	Nutritional needs in space	Research and analysis	Complex nutritional requirements due to physiological changes in space.	Emphasized the need for close monitoring and appropriate nutritional arrangements.
Chaloulakou et al.	2022	Pathophysiological changes due to space environment stressors	Analytical review	Importance of nutrition in mitigating effects like bone and muscle mass loss.	Addressed historical inadequacies in space food and menu fatigue.
Tang et al.	2022	Optimal nutritional intake for extended stays on Mars or the Moon	Research on food forms and allocation	Insights into functional food formulation for long missions.	Proposed strategies for sustainable and efficient nutrition in space exploration.
Kumar & Gaikwad	2023	Advanced food packaging systems for space missions	Review and analysis	Identified essential advancements in space food packaging, crucial for safety and nutrition during missions.	Stressed packaging's role in improving space food quality for long missions.
This study	-	Optimizing astronaut nutrition on space stations	Mathematical modeling with DOE & ANOVA	Developed a model to meet comprehensive nutritional needs in microgravity.	Introduced a tailored approach considering individual health profiles and mission complexities.

DOE: Design of experiments, ANOVA: Analysis of variance.

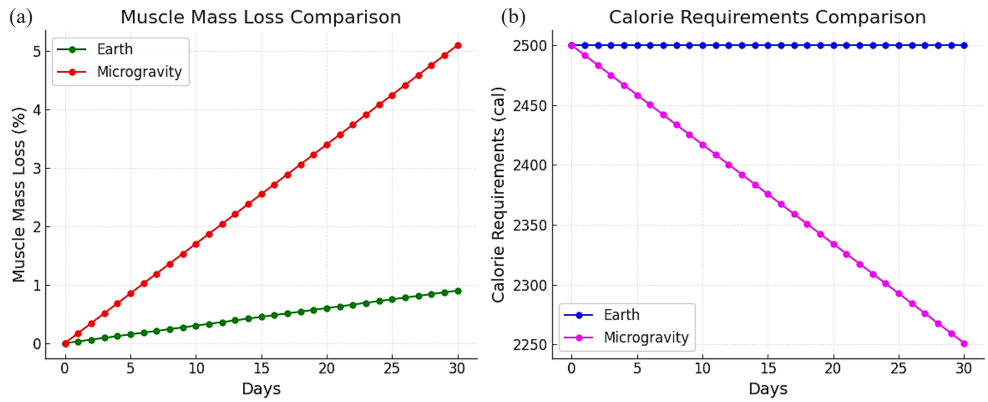

Fig. 1. Comparative analysis of (a) muscle loss and (b) caloric needs in Earth and microgravity environments.

significantly differs from those detailed in Table 1 by offering a tailored and dynamic nutritional strategy, uniquely suited to meet the nuanced physiological demands of astronauts in microgravity. This not only sets a new standard in astronaut nutrition but also directly addresses the complex challenges of maintaining astronaut health and performance in the challenging environment of space. At the same time, this study thoroughly examines the dietary challenges faced during past space missions and the strategies implemented to overcome them. Drawing from these experiences and leveraging seminal literature, the model proposes a scientifically grounded, mathematically precise method to refine the nutritional intake of astronauts. A key innovation of this work is its mathematical modeling approach, which creates highly customized nutrition plans that consider both the astronauts' health profiles and the complex nature of the space missions.

Ultimately, this study underscores the indispensable importance of nutrition optimization in space—a factor that will become increasingly vital as missions grow in duration and complexity. This research is dedicated to equipping astronauts with the tools for optimal nutrition, ensuring their health, and enabling peak performance for the rigors of space travel. Through this mathematical model, which dynamically integrates DOE and ANOVA methodologies, a new standard is being set for supporting the well-being of astronauts in the challenging space environment.

The article is structured as follows: Section 2 discusses challenges and solutions for nutrition in space, focusing on the unique aspects of living in microgravity environments. Section 3 details the mathematical model used for nutrition optimization, including its main components and application. Section 4 elaborates on the implementation and validation of the model, utilizing DOE and ANOVA. Finally, Section 5 presents the results, evaluation, and future directions of the research, highlighting its implications for astronaut health and nutrition in space missions.

2. Challenges and solutions for nutrition in space

2.1 Challenges of life in space

Space is a fascinating environment with endless potential for exploration, representing the curiosity and scientific pursuit of humanity. However, space exploration and sustaining life during prolonged missions bring significant challenges and risks. One major challenge is living and working in space stations where gravity is almost non-existent. The absence of gravity in space significantly affects astronauts' lives, causing substantial physiological impacts on the human body (National Aeronautics and Space Administration, 2018).

2.1.1 Bone and muscle loss

The lack of gravity can lead to bone density and muscle mass loss in astronauts. This weakening of bones and muscles can adversely affect the health and performance of astronauts during long-term space missions. Astronauts require special exercise programs and resistance equipment to prevent bone and muscle loss and maintain bodily endurance. Space agencies provide suitable exercise equipment and programs to mitigate these physiological changes. Additionally, astronauts may need supplements containing vitamins and minerals to support bone health (National Aeronautics and Space Administration, 2018). Continuous research and development are occurring to overcome the challenge of gravity deficiency in space. These efforts aim to ensure that astronauts remain healthy and robust during long missions. Fig. 1 visually represents the effects of microgravity on muscle mass and the associated changes in caloric needs. The graph was generated using Python-based analysis, leveraging data from studies by Di Girolamo et al. (2020) and Liu et al. (2024), which provide detailed insights into the physiological effects of microgravity on muscle atrophy. This comparative analysis between Earth and microgravity environments is essential for optimizing astronaut nutrition and maintaining long-term health in space.

2.1.2 Fluid and electrolyte balance

The absence of gravity in space can also affect the body's fluid and electrolyte balance. Without gravity, the upward movement of body fluids is restricted, increasing the risk of health issues like urinary tract stones. Hence, astronauts need to pay special attention to their water intake, which is crucial for bodily functions and maintaining electrolyte balance (National Aeronautics and Space Administration, 2022).

2.1.3 Radiation exposure

Exposure to harmful radiation sources, such as solar rays and cosmic radiation, is another major concern in space. Long-term exposure to these types of radiation can lead to serious health problems. Astronauts are protected by radiation shields provided by space vehicles and stations, and various measures are taken to minimize radiation exposure (European Space Agency, 2017).

2.1.4 Food and nutrition

Food supplies in space missions are limited, and the shelf life of foods is restricted. As shown in Fig. 2, astronauts have specialized nutrition programs and activities for long-term missions. These programs are meticulously prepared to provide essential nutrients. Foods are stored in compressed, dried, or vacuum-packed forms to make them suitable for consumption in space (Smith et al., 2021). The image in Fig. 2 was generated using OpenAI's DALL E model and visually represents the structured approach to space nutrition.

2.1.5 Psychological effects

Prolonged isolation and confined spaces can negatively impact astronauts' psychological health. Space agencies provide psychological support and offer programs to help astronauts develop stress-coping skills (Vakoch, 2011).

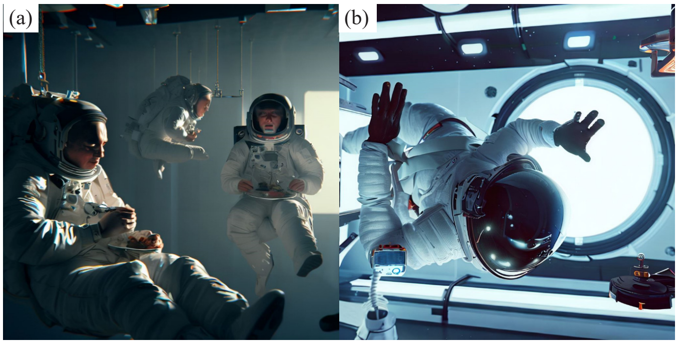

Fig. 2. (a) A representative moment of an astronaut's nutrition in a space station, (b) A representative outdoor activity of an astronaut in a space station.

2.1.6 Plant cultivation

Cultivating plants in space provides fresh food and contributes to oxygen production. Plant cultivation technologies are crucial for long-term missions in space. Nutrition challenges in space create a continuous area for research and development, aiming to maintain health and performance during prolonged missions. Space agencies and scientists continually work on new strategies and technologies to overcome these challenges, enhancing the interest and potential of humanity's space explorations (National Aeronautics and Space Administration, 2023).

2.2 Nutritional strategies for space missions

Nutrition in space is not only a necessity for astronauts' health but also a key to the success of long-term space missions. The unique challenges faced by the human body in this extreme, microgravity environment necessitate special considerations for nutrition. NASA's nutrition standards for 90-180 day missions, established in the 1990s, address these unique challenges. Initially covering basic nutrient requirements, these standards have evolved to be more detailed and specific over time. Table 2 provides a detailed list of the amounts of protein, carbohydrates, vitamins, and other essential nutrients required for astronauts on different mission types. Factors like fluid intake and electrolyte balance become much more critical in space, as do the levels of radiation, which can affect nutritional needs, especially vitamin intake (Smith et al., 2021).

The storage of nutrients in space is a significant issue. Food storage methods on Earth may not always be applicable in the harsh conditions

Table 2.
Nutritional requirements defined for The International Space Station (ISS) and exploration missions (Smith et al., 2021).

Nutrient	ISS requirements (1996)	Discovery requirements (2005)	Exploration requirements (2020)
Energy	12-15%	0.8 g/kg body weight	1.2-1.8 g/kg body weight
Protein	12-15%	35%	40%
Carbohydrate	50-55%	50-55%	45-65%
Fat	25-35%	20-35%	20-35%
omega-6 fatty acids	N/A	14 g	1.1-1.6 g
Omega-3 fatty acids	N/A	1.1-1.6 g	1.1-1.6 g
Saturated fat	As low as possible	ALARA, <10% total calories	ALARA, <10% total calories
Trans Fat	N/A	As low as possible	ALARA, <1% total calories
Cholesterol	N/A	<300 mg	10-14 g/1000 kcal
Fiber	N/A	Women: 25 g, Men: 38 g	Women: 25 g, Men: 38 g
Fluid	1-1.5 mL/kcal	32 mL/kg body weight	>2000 mL
Vitamin A	1000 µg RE	700-900 µg RE	1000 IU (25 µg)
Vitamin D	10 µg	25 µg	25 g
Vitamin K	80 µg	Women: 90 µg, Men: 120 µg	Women: 90 µg, Men: 120 µg
Vitamin E	20 mg tocopherol equivalents	15 mg tocopherol equivalents	15 mg Tocopherol Equivalents
Vitamin C	100 mg	90 mg	Women: 110 mg, Men: 125 mg
Vitamin B12	2.0 µg	2.4 µg	2.4 µg
Vitamin B1	2.0 mg	1.7 mg, 1.3 mg	1.3 mg
Thiamine	1.5 mg	Women: 1.1 mg, Men: 1.2 mg	Women: 1.1 mg, Men: 1.2 mg
Riboflavin	2.0 mg	Women: 1.3 mg, Men: 1.1 mg	Women: 1.3 mg, Men: 1.1 mg
Folic Acid	400 µg	400 µg	400 µg
Niacin	20 mg NE	16 mg NE	Women: 14 mg NE, Men: 16 mg NE
Biotin	100 µg	30 µg	30 µg
Pantothenic Acid	5 mg	30 mg	5 mg
Choline	N/A	N/A	Women: 425 mg Men: 550 mg
Calcium	1,200 – 2,000 mg	1,200 – 2,000 mg	1,200 – 2,000 mg
Phosphorus	≤ 1.5 x calcium intake	700 mg, and ≤ 1.5 x calcium intake	700 mg, and ≤ 1.5 x calcium intake
Magnesium	350 mg	Women: 320 mg Men: 420 mg	Women: 320 mg Men: 420 mg
Sodium	1,500 – 3,500 mg	1,500 – 2,300 mg	1,500 – 2,300 mg
Potassium	3,500 mg	4.7 g	Women: 2600 mg Men: 3400 mg
Iron	< 10 mg	8 – 10 mg	8 mg/d for men and women, 18 mg/d for women under 50 who do not pharmacologically suppress menstruation
Copper	1.5 – 3.0 mg	0.5 – 9 mg	900 µg
Manganese	2 – 5 mg	Women: 1.8 mg Men: 2.3 mg	Women: 1.8 mg Men: 2.3 mg
Fluoride	4.0 mg	Women: 3 mg Men: 4 mg	Women: 3 mg Men: 4 mg
Zinc	15 mg	11 mg	Women: 8 mg Men: 11 mg
Selenium	70 µg	55 – 400 µg	55 µg
Iodine	150 µg	150 µg	150 µg
Chromium	100 – 200 µg	35 µg	Women: 25 µg Men: 35 µg
Chloride	N/A	N/A	2300 mg
Molybdenum	N/A	N/A	45 µg

ALARA: As low as resonably achievable, N/A: Not applicable, RE: Retinol equivalent, IU: International Units, NE: Niacin Equivalent of space. In space, the shelf life of nutrients is limited, and special storage techniques are needed to preserve their nutritional value. Moreover, the difficulties astronauts face in consuming food items in space alter the way food is prepared and consumed. Space agencies continually develop new technologies and methods to meet nutritional needs in space, crucial for maintaining astronauts' health and ensuring the success of space missions. Nutrition in space, therefore, remains a vital component of space research, and ongoing studies in this area are crucial for enabling astronauts to undertake longer missions in space. The consumption of 8 specific types of food by astronauts reflects these nutritional strategies (Perchonok et al., 2012):

- Lyophilized Meat: Dehydrated meat, suitable for long-term storage, becomes ready for consumption after rehydration and is an important protein source.
- Semi-Stable Dairy Products: Dairy products processed to withstand space conditions, providing essential nutrients like calcium and protein.
- Rehydratable Vegetables: Freeze-dried vegetables that can be stored long-term and easily consumed with added water, providing fiber, vitamins, and minerals.
- Thermally Stabilized Meals: Heat-processed meals stored in special packaging, important for variety and nutrition.
- Granola Bars: Ideal for meeting energy needs in space, granola bars offer a quick and convenient snack.
- Baked Bread Alternatives: Alternatives like tortillas meet bread needs without creating crumbs, suitable for microgravity.
- Fruit Purees: Important alternatives for vitamins and minerals, given the difficulty of finding fresh fruit.
- Ready-to-Drink Beverages: Packaged drinks like fruit juices, coffee, and tea, prepared by mixing with water.

Each of these foods is part of the nutrition strategies designed for the success of space missions. Balanced and adequate nutrition is essential for maintaining health and performance. Nutrition in space is critical not only for physical health but also for morale and psychological well-being. Thus, food selection and preparation techniques continue to be a significant part of space research.

3. Nutrition optimization model in microgravity environment

Nutritional optimization in a space environment is a mathematical model used to ensure that astronauts maintain a healthy diet and maximize their physical performance. This model is designed to account for astronauts' daily nutritional needs, energy requirements, protein intake, and vitamin and mineral consumption, and plays a crucial role in sustaining astronaut health and efficiency in the challenging conditions of space. Here are some of the main components of this nutrition optimization model:

- Energy Requirement Calculation: The daily energy needs of astronauts are calculated based on factors such as age, gender, weight, height, and activity levels. During space missions, the absence of gravity can lead to variations in energy consumption.
- Macronutrient Distribution: The model determines the needs for carbohydrates, proteins, and fats for astronauts. Protein intake is crucial during space missions to prevent muscle loss and maintain bodily functions.
- Vitamin and Mineral Intake: The space environment can affect the absorption of certain vitamins and minerals. Therefore, the model calculates the amounts of specific foods to ensure adequate intake of these nutrients.
- Space-Specific Factors: The nutrition optimization model considers the unique conditions in space. For example, astronauts are at risk of bone density loss due to the lack of gravity, making calcium and vitamin D intake important.
- Constraints of Food Resources: There is limited food resource on space stations. Thus, the model optimizes the quantities of specific foods to ensure the efficient use of food stocks during prolonged missions.

This section meticulously outlines the mathematical model employed to optimize the nutrition of astronauts aboard space stations. This model represents an integrative tool tailored to address the nutritional demands of spacefarers, encompassing energy, protein, and essential vitamins and minerals. The model's structure is informed by the unique environmental challenges of space, necessitating careful balance and precise tailoring of dietary regimens. At the core of the model's development is the DOE, a strategic framework used to plan and conduct experiments efficiently. Through DOE, variables affecting astronauts' nutrition are systematically manipulated to evaluate their impact on health outcomes. This approach allows for the identification of critical factors that significantly influence dietary needs and the interactions between them. The model further incorporates ANOVA, a statistical method to discern the differences between group means and their associated procedures. ANOVA is pivotal in the validation process of the nutritional model, evaluating whether the changes in astronauts' dietary intake (based on the model) have a statistically significant effect on health markers. By comparing the variability within and between experimental groups, ANOVA helps in fine-tuning the model to account for variabilities in metabolic responses among different astronauts. The optimization aspect of the model is dynamically adjusted, accommodating continuous input from ongoing health monitoring. This adaptive feature allows for the recalibration of dietary plans in response to long-term health data and the adjustment to microgravity's physiological effects. It is a living model, evolving with each mission to incorporate the latest findings in space nutrition science and the logistical realities of food supply in space. By leveraging DOE and ANOVA, the model not only prescribes nutritional strategies but also iteratively enhances its predictive accuracy. Each mission's data contributes to a growing body of knowledge, ensuring that future dietary guidelines are increasingly refined and personalized for the health and performance optimization of astronauts.

3.1 Rationale of objective function and literature background

In nutrition-based optimization problems, objective functions are meant to minimize gaps between nutrition necessities and intakes in addition to balancing caloric and macronutrient intake (Smith et al., 2021; Kumar et al., 2022). Many works on nutrition optimization consider just single objectives related only to, for example, purely protein intake or holistic caloric balance. Long-term manned missions, however, require consideration of all the given parameters:

- Preservation of muscle mass and maintenance of bone density (Hackney et al., 2015)
- Adequate intake of micronutrients to avoid deficiencies in microgravity (Smith & Zwart, 2021)
- Limited food resources and degradation during storage (Perchonok et al., 2012; Kumar & Gaikwad, 2023)
- Activity needs to counteract deconditioning induced by microgravity (Chaloulakou et al., 2022).

While some models do address parts of these individual factors in isolation, such as muscle atrophy or fluid shifts, holistic frameworks that integrate macronutrients, micronutrients, energy balance, and physical activity, all in the context of microgravity, are limited. A few space nutrition models, such as those reported by Smith et al. (2021) for the ISS, exist to date, which provide only baseline dietary guidelines without explicit nonlinear interactions among vitamins, minerals, and activity levels (Bychkov et al., 2021). Additionally, constraints due to food degradation over time and the diversity of consumption needed to maintain diet sustainability in space are not comprehensively modeled in earlier approaches (Tang et al., 2022; Pandith et al., 2023). To that effect, we have designed an integrated multi-objective function to guarantee the sufficiency of daily macro- and micronutrient intake while, in real time, it will minimize deviations from ideal intake, consider food resource constraints, and take into consideration activity distribution. The idea is to model the trade-offs between meeting exact nutrient targets, preserving food quality, and adapting to individual physiological responses for a robust approach to space nutrition that encompasses much more than what single-criterion or purely linear models can (Oluwafemi et al., 2018).

3.2 Model components and objective function structure

The objective function proposed in this study incorporates six interconnected objectives, each of which reflects the different constraints of space missions, as described by Equation 1. This is designed to meet nutrient deficiencies, caloric requirements, bone health needs, and food degradation processes.

1. Nutrient Requirement Objective: This minimizes the deviation between actual intake and recommended daily levels of essential nutrients, including proteins, fats, carbohydrates, vitamins, and minerals.
2. Energy Balance Objective: Ensures astronauts meet daily energy requirements, critical for maintaining muscle mass and supporting immune function (Hackney et al., 2015).
3. Nutrient Limit Objective: Keeps nutrient intake within allowable ranges, avoiding oversupply (e.g., excessive sodium).
4. Vitamin and Mineral Balance Objective: Addresses microgravity-driven changes in absorption, ensuring critical vitamins (Vitamin D, K, etc.) and minerals (iron, calcium) remain at optimal levels (Smith & Zwart, 2021).
5. Nutrient Degradation Objective: Maintains the nutritional integrity of the food over time, one factor often overlooked in traditional Earth-bound dietary models. Perchonok et al. (2012); Kumar & Gaikwad (2023). Activity Requirement Objective: Prevents muscle atrophy and bone loss by prescribing an optimal mix of exercise, as stated by NASA (2022), integrated into the dietary plan for synergy.
6. By unifying these objectives, our comprehensive approach diverges from existing methods that mainly target either macronutrient targets or energy balance independently. The holistic structure of the current model and, at its core, the ability to dynamically couple nutrient intake with physical activity schedules provides the assurance that astronauts will maintain muscle mass, bone density, and overall metabolic health. These are some of the most important concerns in prolonged microgravity conditions (Bychkov et al., 2021).

Works such as those by Hackney et al. 2015 and Smith & Zwart 2021 bring forth the need for proteins, vitamins, and minerals regarding muscle and cardiovascular health but rely on separate modules for diet versus activity planning. Kumar & Gaikwad, 2023, show that food degradation and packaging have to be factored in but do not address its integration with day-to-day nutrient balancing.

Tang et al. (2022) discussed food formulation strategies but did not provide a dynamic model that unifies exercise schedules with nutrient consumption. Similarly, Perchonok et al. (2012) highlighted constraints on shelf life that are not usually modeled in nutrition.

In this paper, the proposed objective function is the next-generation approach that will actually synthesize those hitherto separated concerns into one mathematical framework. Our model brings together multi-criteria decision making into the fold of microgravity-specific challenges, ensuring a sustainable and data-driven solution for long-duration space missions.

3.3 Design of experiments

DOE is an essential statistical tool used for planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that may influence a particular outcome (Yeole & Parthasarthy, 2022). In the context of nutrition optimization for astronauts, DOE can be utilized to ascertain the best combination of nutrients that contributes to optimal health and performance in a microgravity environment. A full factorial experimental design was chosen, examining three levels (low, medium, high) of key factors, such as macronutrient ratios (proteins, carbohydrates, fats), micronutrient concentrations, and total caloric intake. This resulted in a total of 27 experimental runs to cover all possible combinations. Each experimental run was evaluated based on its impact on key performance indicators, such as muscle retention, energy balance, and overall metabolic health. The DOE results informed the calibration of the model by identifying the factors and interactions that had the most significant effects on these outcomes. The statistical significance of these factors was determined using ANOVA, which provided the basis for finalizing the model's parameters.

Key elements of DOE in nutrition optimization

- Experimental Design: Development of a series of tests where intentional changes were made to the input variables of a nutritional model to observe the corresponding changes in outcomes. This could include varying levels of macronutrients, micronutrients, and caloric intake.
- Factor Selection: Identification of critical dietary factors (like protein, carbohydrates, fats, vitamins, and minerals) and environmental conditions unique to space travel that could affect astronaut health.
- Response Variables: These are the health and performance metrics of astronauts, which could include muscle mass, bone density, energy levels, and cognitive performance.
- Randomization: Ensuring that the trials are randomized to prevent bias in the nutrient intake and environmental conditions.
- Replication: Repeating the experiments to quantify the natural variation in the response and to increase the precision of the results.

DOE implementation steps

1. Define the objectives of the experiment clearly, such as understanding the impact of nutrient variations on astronaut health.
2. Select and quantify the factors, levels, and ranges to be tested.
3. Choose an appropriate experimental design (e.g., full factorial, fractional factorial, or response surface methodology).
4. Execute the experiments while carefully controlling other influential factors.
5. Collect and analyze the data using appropriate statistical methods.

By using DOE, researchers can systematically investigate the nutritional needs of astronauts, taking into account the complex interactions between various dietary components and the unique challenges posed by the microgravity environment.

3.4 Notations

Below are the variables and parameters used in the astronaut nutrition optimization model:

3.4.1 Indices:

i: Index representing a specific nutrient. (i = 1, 2, ..., N)
i_v: Index representing a specific vitamin. ($i\_v \subset i$)
j: Index representing a type of food. (j = 1, 2, ..., M)
k: Index representing a time period within the planning duration. (k = 1, 2, ..., T)

3.4.2 Variables:

x_j: Amount of food type j consumed by the astronaut.
y_k: Time spent on each astronaut activity (k, represented by the activity index).

3.4.3 Parameters:

N_i: Daily requirement of the astronaut for nutrient i.
A_{ij}: Amount of nutrient i in food type j.
U_i: Maximum consumption amount for the astronaut to obtain nutrient i.
E_j: Energy content in food type j.
E_{min}: Minimum energy amount that must be met by the astronaut.
$V_{(i\_v)j}$: Amount of vitamin i_v in food type j.
W_j: Total vitamin content in food type j.
Y_{max}: Maximum duration for activities in specific time periods.
$Y_{min:}$ Minimum duration for activities in specific time periods.

T_j: A consumption preference for food type j.
T_{min}: Minimum total value of Tj that the model must meet.
S_j: A score or rating assigned to food type j.
S_{min}: Minimum total score limit in the model.
S_{max}: Maximum total score limit in the model.
H_2O_j: Water content in food type j.
H_2O_{min}: Minimum daily water intake required for the astronaut.
H_2O_{max}: Maximum daily water intake required for the astronaut.
Vr_{max}: Maximum diversity.
Vr_{min}: Minimum diversity.
Vr_j: Diversity coefficient associated with food type j.
C_j (t): Time-varying quality change amount for food type j.
C_{j0}: Initial quality value for food type j.
k_j (t): Time-varying quality change rate for food type j.
α: Energy Balance Coefficient.
β: Deviation Balancing Coefficient.
γ: Weight-Value Relationship Coefficient.
δ: Target Deviation Balancing Coefficient.
λ: Quality Change Balancing Coefficient.

3.5. Model

The proposed integrated problem is formulated as a nonlinear programming (NLP) model that aims to minimize the objective function and optimize the decision variables. The NLP model, inclusive of integers and components, presents a comprehensive framework for the complex problem at hand. It provides a broad structure to address the complexity of our problem.

Objective function:

$$Min\ Z = \sum_i \left| N_i - \sum_j A_{ij}\ x_j \right| + \alpha . \sum_j E_j . x_j + \beta . \sum_i \sum_j \left(\frac{x_j}{U_i} - \frac{x_j}{N_i} \right)^2 + \gamma . \sum_j \left| W_j - \sum_i V_{(i\_v)j} . x_j \right| - \lambda . \sum_j (ln\ C_{j0} - k_j(t)) . x_j + \delta . \left(\sum_k (Y_{max_k} - Y_{min_k}) . y_k + \sum_k \left| y_k - Y_{min_k} \right| \right) \quad (1)$$

Constraints:

$$N_i \le \sum_j x_j . A_{ij} \le U_i \quad , \quad \forall i \quad (2)$$

$$\sum_j x_j . E_j \ge E_{min} \quad (3)$$

$$Y_{min_k} \le y_k \le Y_{max_k} \quad , \quad \forall k \quad (4)$$

$$Vr_{min} \le \sum_j Vr_j . x_j^2 \le Vr_{max} \quad (5)$$

$$\sum_j T_j . \log(x_j + 1) \ge T_{min} \quad (6)$$

$$S_{min} \le \sum_j x_j . S_j \le S_{max} \quad (7)$$

$$H_2O_{min} \le \sum_j x_j . H_2O_j \le H_2O_{max} \quad (8)$$

$$C_j(t) \cdot x_j \le C_{j0} \cdot e^{-k_j(t)} \quad , \quad \forall j \quad (9)$$

$$x_j , y_k \ge 0 \quad , \quad \forall_{j,k} \quad (10)$$

The objective function of the model aims to minimize nutrient deficits and maximize energy efficiency. The value of this function represents the optimal balance between macronutrient intake, micronutrient absorption, and caloric needs. The function is calibrated to prioritize muscle retention, bone health, and overall metabolic stability, addressing the unique challenges of microgravity. The objective function (1) of the proposed model consists of 6 items. These are:

- Nutrient Requirement Objective: This objective focuses on minimizing the discrepancies between the daily nutrient requirements of astronauts and the actual amount consumed. It aims to ensure that astronauts' daily nutrient needs are met optimally.
- Energy Balance Objective: This objective targets fulfilling the energy requirements of astronauts by balancing the consumed energy amount. It focuses on maintaining the daily energy balance, ensuring that astronauts meet their energy needs effectively.
- Nutrient Limit Objective: This objective ensures that the consumption of each nutrient stays within predefined minimum and maximum limits. It helps maintain a balanced intake of each nutrient, ensuring that astronauts consume them within certain limits.
- Vitamin and Mineral Balance Objective: This objective aims to match the daily requirements of each vitamin and mineral with the amount consumed. It ensures the optimization of astronauts' vitamin and mineral intake, addressing specific nutritional needs.
- Nutrient Degradation Objective: This objective addresses the degradation processes of each nutrient over the storage period and their impact on consumption quantities. It aims to maintain the initial quality and account for the rate of degradation of nutrients over time. The goal is to preserve the quality and nutritional value of food items at the highest possible level. This approach is particularly relevant for scenarios like long-duration space missions, where maintaining the nutritional integrity of food supplies is critical for astronaut health. This objective ensures that nutrients are kept in the best possible condition, minimizing degradation over time.
- Activity Requirement Objective: This objective is to comply with the minimum and maximum time limitations set for astronauts' activities in specific time intervals. It seeks to optimize the astronauts' activities within these defined limits, contributing to their overall well-being and performance. The goal is to optimize four key types of activities within these time constraints, thereby enhancing the astronauts' overall well-being and performance:
  - Aerobic Exercise: Utilizing equipment like treadmills or stationary bicycles for cardiovascular health.
  - Resistance Training: Engaging in exercises that maintain muscle mass and bone density is crucial in a microgravity environment.
  - Flexibility and Balance Workouts: Incorporating routines like adapted yoga or pilates to support joint health and body coordination.
  - Skill-Based or Recreational Activities: Including activities like virtual reality simulations or light physical games for mental well-being and leisure.

The constraints of the proposed model are as follows:

- Nutrient Requirement Limitations (2): For each nutrient, the consumed amount must comply with daily needs and maximum limits. This constraint restricts astronauts from consuming each nutrient beyond a certain range and ensures these amounts stay within specified limits.
- Total Energy Consumption Limitation (3): The total energy consumption must meet the daily energy needs of the astronauts. This ensures that astronauts meet their energy requirements.
- Activity Limitations (4): The activities of the astronauts for each time period must adhere to the determined minimum and maximum time limitations. This ensures that astronauts optimize their activities within specified durations.
- Food Group Balance (5): Applied to maintain the balance of food types according to a certain group or category. This constraint ensures the necessary nutrient groups are consumed adequately and prevents overconsumption.

- Consumption Diversity Limitation (6): This constraint encourages the diversity of consumed food. Tj, a logarithmic function, decreases the marginal value of increases in consumption, rewarding diversity. A diverse diet ensures the intake of all necessary micro- and macronutrients, preventing the adverse effects of a monotonous diet.
- Salt Restriction (7): This constraint is placed to keep the consumed amount of sodium within a certain range. Excessive sodium consumption during long-term space missions can lead to health issues. Thus, controlling sodium intake is essential.
- Water Restriction (8): This constraint regulates daily water consumption. Water is critical for vital functions. Balanced water consumption is particularly essential in a closed space environment.
- Nutrient Degradation Constraint (9): This constraint ensures that the effective concentration of each nutrient j does not fall below its degraded level over time, considering the quantity consumed. Specifically, $C_j(t)$ represents the effective amount of nutrient j available after degradation at time t, while $C_{j0} \cdot x_j \cdot e^{-k_j(t)}$ models the expected decrease in its concentration due to degradation, where C_{j0} is the initial concentration and $e^{-k_j(t)}$ describes the decay over time. This constraint is crucial to ensure that the nutritional value of the food consumed remains within an acceptable range over the storage period, particularly important in environments like space missions where resource replenishment is limited.

3.6 Model validation and enhancement using ANOVA

After constructing a nutrition optimization model for astronauts in a microgravity environment, it's imperative to validate the model's performance and enhance it based on the results obtained from various simulations or real-world applications. The ANOVA technique becomes a pivotal tool in this phase. ANOVA is a statistical method used to compare the means of three or more samples to understand if at least one sample mean is significantly different from the others. This can provide insights into the variability of the model's output and the factors most significantly impacting the nutritional outcomes.

3.6.1 Application of ANOVA in model validation

- Assessment of Variability: ANOVA is employed to analyze the variability in the model's outputs to determine the consistency and reliability of the nutrition optimization model across different scenarios.
- Factorial Effects: Through the use of factorial experiments, ANOVA can assess the main and interaction effects of the factors involved in the model (such as different food types, nutrient levels, and activity durations).
- Model Enhancements: The insights gained from ANOVA can lead to modifications in the optimization algorithms or adjustments in the input parameters to improve the model's accuracy and robustness.
- Hypothesis Testing: ANOVA tests specific hypotheses about the relationships between the factors and the nutritional outcomes, allowing researchers to refine the model based on statistical evidence.
- Model Fidelity: By comparing groups, such as predicted versus actual nutritional outcomes, ANOVA helps in evaluating the fidelity of the model and identifying any discrepancies that need attention.

3.6.2 Implementation in the optimization model

In the context of the astronaut nutrition optimization model, ANOVA could be used in the following ways:

- Identify Key Nutrients: Determining which nutrients have the most significant impact on astronaut health and should, therefore, be prioritized in the optimization process.
- Optimal Food Combinations: Evaluating different combinations of food types to ascertain which combinations yield the best nutritional balance.
- Activity-Diet Interaction: Understanding how different levels of physical activity might interact with dietary intake to affect the overall nutritional status.
- Resource Allocation: Helping in making decisions about the allocation of limited resources, such as which food supplies to maximize or minimize based on their nutritional impact and the variability of needs during the mission.

Overall, ANOVA serves as a crucial step in validating and enhancing the nutrition optimization model, ensuring that it can effectively support the health and performance of astronauts under the unique conditions of space travel.

4. Application

This section addressed the optimization of astronaut nutrition in microgravity, employing DOE and ANOVA. Model coefficients were determined through DOE, while ANOVA was utilized to analyze the variance in model outputs, revealing significant nutritional factors and their interactions. The heuristic method of random search was applied to solve the complex nutrition optimization problem, thoroughly exploring a broad solution space. The results of the model were presented in detail, providing a comprehensive understanding of the impact of each variable and coefficient on the model. These results included critical performance indicators such as objective values, GAP, and solution time. The section also encompassed the pseudocode used to understand the algorithm's functioning, illustrating the step-by-step implementation of the method.

In this study, focusing on optimizing astronaut nutrition, our data, which include specific parameters on types of food and activity durations, are carefully selected to cater to the unique needs of astronauts. These data, based on average values for a male astronaut of ideal weight and height, are not only informed by thorough analyses of NASA's reports (National Aeronautics and Space Administration, 2018; National Aeronautics and Space Administration, 2022; Smith et al., 2021) and standard nutrition science practices but also enriched by consultations with expert dietitians. Data from the National Aeronautics and Space Administration (2018) on energy requirements, macronutrient distribution (protein, fat, and carbohydrate needs), and micronutrient necessities were extracted to establish the baseline nutritional requirements for astronauts. This reference provided crucial insights into how microgravity affects nutrient metabolism, absorption, and utilization, which were used to define the parameters and constraints of the model. The National Aeronautics and Space Administration (2022) contributed to empirical data on the physiological impacts of microgravity, such as muscle atrophy and bone density loss. The model incorporated these findings to adjust the daily requirements of critical nutrients like calcium, vitamin D, and protein, aiming to mitigate muscle and bone loss during space missions. Smith et al. (2021) offered NASA's recommended dietary allowances and guidelines for food storage and shelf life in space. These standards were essential for setting practical constraints within the model, including limits on caloric intake, nutrient density, and food diversity. The data ensured that the model's outputs aligned with the real-world nutritional needs of astronauts during lengthy space missions. These professionals bring invaluable insights, particularly in the context of space travel nutrition. In addition to this, our project team is committed to continuous improvement through ongoing experimental studies. The methodology and the integration of this comprehensive data into our model have clearly been depicted in Fig. 3, which serves to elucidate our methodical approach in developing effective nutrition strategies for astronauts, combining scientific rigor with practical expertise. This figure was generated using OpenAI's DALL E model, with the flowchart and text elements added manually using Adobe Illustrator. In Fig. 3, the relevant steps are as follows:

1. Initial Data Gathering and Analysis
2. DOE for Coefficient Determination
3. Implementation of Random Search Algorithm for Solutions
4. Objective Function Evaluation at Various Points
5. Assessment and Reporting of Findings

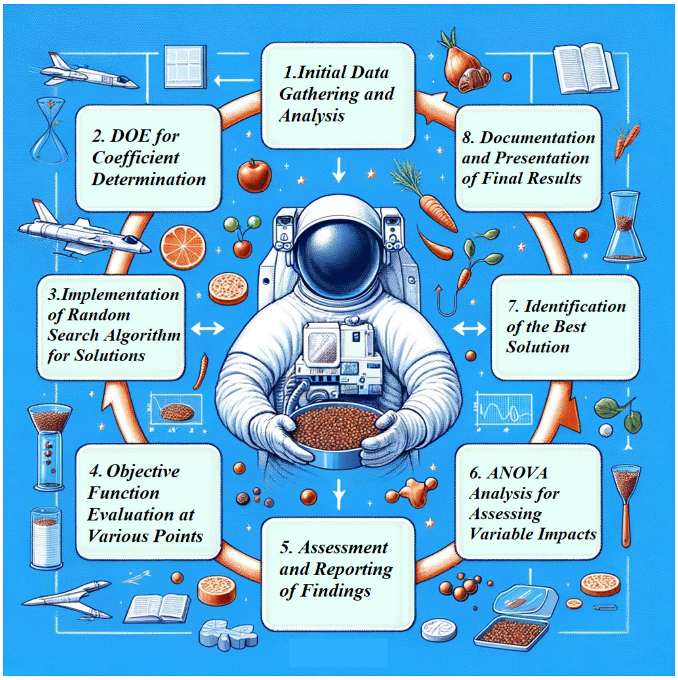

Fig. 3. Methodology flowchart for astronaut nutrition optimization study. ANOVA: Analysis of variance.

```
BEGIN
Select a random starting solution
Evaluate the objective function at this point
FOR each iteration IN the predetermined number of iterations
Generate a new solution point randomly
Evaluate the objective function at the new point
IF the new solution is better than the current solution
Update the current solution with the new one
ENDIF
ENDFOR
Return the best solution
END
```

Fig. 4. Pseudo code of the random search heuristic algorithm.

6. ANOVA Analysis for Assessing Variable Impacts
7. Identification of the Best Solution
8. Documentation and Presentation of Final Results

These steps and the flowchart have been included in the academic paper to provide a clear understanding of how the model is applied.

4.1 DOE solution

This section offers a detailed examination of how the model's coefficients (α, β, γ, δ, λ) were determined by DOE. Three different levels - low, medium, and high - were predefined for each coefficient. Each combination of these levels was meticulously analyzed to assess their effects on the model. Metrics defined for measuring the model's performance included various nutritional factors, such as energy balance, nutrient balance, vitamin diversity, and water consumption. The outputs of the model for each combination were analyzed, thoroughly examining the impact of the coefficients on the model's outcomes. These analyses played a crucial role in identifying critical coefficients, particularly in meeting specific nutritional requirements and maintaining energy balance. As a result, setting the α and β coefficients at 1.0 emphasized the model's focus on energy and nutrient balance, while setting γ, δ, and λ coefficients at lower values (0.5) resulted in less weight being given to other factors such as vitamin diversity and water consumption. This balanced approach provided critical insights into how the model could be tuned to effectively meet astronauts' nutritional needs. The comprehensive analysis demonstrated how the model could adapt to various scenarios and nutritional requirements, offering valuable insights into optimizing astronaut health and performance during space missions.

4.2 Employed algorithm and application process

This section details the explanation and implementation process of the random search heuristic algorithm used in the solution of the model. The algorithm is designed to efficiently explore the extensive solution space in nutritional optimization problems and includes the steps mentioned in Fig. 4.

This algorithm, with its simple and flexible structure, is well-suited for complex, multidimensional nutritional optimization problems. Random search offers an ideal approach for complex situations like space missions with uncertain and variable nutritional requirements. These features of the algorithm enhance the model's applicability and effectiveness, supporting nutritional and activity planning critical for optimizing astronaut health and performance during space missions. To address concerns regarding the reliability of using random search heuristic methods, the model's robustness was verified through multiple validation techniques.

- Cross-Validation: The model underwent extensive cross-validation, where multiple simulations were run with varying initial conditions to ensure consistent outcomes across different scenarios.
- Sensitivity Analysis: A sensitivity analysis was performed to identify the most influential parameters affecting the model's results. By focusing on these critical variables, the model's reliability and accuracy were enhanced.
- Comparative Analysis: The model's outcomes were compared against historical data and established nutrition standards for space missions. This comparison demonstrated that the model provides plausible and consistent results aligned with current scientific knowledge and space agency guidelines.

4.3 Mathematical model solution

This section thoroughly examines the solution process of the astronaut nutrition optimization model and the employed random search heuristic method. This method is preferred for efficiently exploring a wide solution space and finding solutions to complex nutritional optimization problems. Each step of the algorithm involves randomly selecting consumption quantities of food types and durations of activities, evaluating these values in the model, and identifying the most suitable solution. The numerical results obtained from the model's solution demonstrate the complexity of nutrition optimization and the model's effectiveness in meeting various nutritional needs. For example, the consumption quantities of certain food types and allocated times for activities reveal how astronauts' energy needs and nutritional balances are met. The results offer valuable insights into how the model can be adjusted to optimize astronaut health and performance during space missions. This detailed analysis includes the application of the random search heuristic methods and the interpretation of the results obtained, providing an in-depth understanding of the model's applicability and effectiveness. To implement our nonlinear programming model, we mainly used:

- Python 3.9 (Anaconda distribution) for coding, data preprocessing (via NumPy, Pandas), and result visualization.
- The main solver: Gurobi Optimizer v9.5 due to its great capability in handling large-scale optimizations involving mixed-integer nonlinear programming problems. Solutions were cross-checked against open-source solvers like COBYLA and SLSQP from SciPy. optimize.
- A Random Search Heuristic, in Python that could quickly explore the solution space and provide an initial candidate solution to Gurobi. (Section 4.2).
- All the computations were run on a workstation equipped with an Intel® Core™ i7 CPU, 16 GB RAM, and Windows 10 (64-bit). Typical runs converged (GAP ~2.5%) within 2-4 hours depending on the problem's complexity.

The detailed results obtained from the model's solution are examined through food consumption quantities and activity durations presented in Tables 3 and 4. Table 3 presents the results of model validation, showing the optimized intake for eight different food types. The extraction and analysis methods were based on DOE and ANOVA, which confirmed the significance of each nutrient in preventing muscle atrophy and ensuring energy balance. For example, rehydratable vegetables were found to be essential for energy density and nutrient absorption, particularly for vitamins and minerals crucial for muscle maintenance. The consumption quantities of each food type demonstrate how astronauts' daily energy and nutrient needs are met in a balanced manner. For instance, the high consumption quantity of Food Type 3 (4.00 units) may indicate that this food is an energy-dense option. Such details are critical in preventing muscle loss and maintaining overall health during space missions. Values in Table 4—covering Aerobic Exercise, Resistance Training, Flexibility/Balance Workouts, and Skill-Based/Recreational Activities—were determined by balancing astronauts' physiological needs with mission-specific constraints. The model references established guidelines for mitigating microgravity-induced muscle and bone loss (NASA, 2022) to set minimum durations for aerobic and resistance exercises, while mission parameters (e.g., equipment schedules and crew work shifts) cap the total activity time. The optimization problem solved within these dual constraints results in feasible durations that protect health while meeting operational limitations. Activity durations provide essential information on how much exercise astronauts need to do during space missions. Regular physical activity is mandatory for maintaining muscle and bone density during prolonged stays in space. The activity durations proposed by the model are optimized to meet this need. The performance values in Table 5 demonstrate the model's effectiveness and applicability. The low GAP value and acceptable solution time indicate that the model offers reliable and practical solutions. These results provide a comprehensive understanding of how the model and the proposed

Table 3.
Consumption amounts of food types.

Food type	Consumption amount*100 gr
Lyophilized meat	0.700
Semi-stable dairy products	2.370
Rehydratable vegetables	4.000
Thermally stabilized meals	0.120
Granola bars	1.990
Baked bread alternatives	1.040
Fruit purees	0.100
Ready-to-drink beverages	4.920

Table 4.
Activity durations.

Activity	Duration (hour)
Aerobic exercise	3.900
Resistance training	1.680
Flexibility and balance workouts	2.350
Skill-based or recreational activities	1.050

Table 5.
Model solution performance values.

Value type	Value
Objective function value	199928.863
GAP value	%2.5
Solution time	2.34 h
Number of iterations	10000

approach can meet astronauts' nutritional and physical activity needs during space missions. The objective function value is 199,928.863, which is the measure of how well the model could balance nutrient needs, caloric intake, and activity constraints; a lower score is better. A 2.5% GAP suggests that the output from the solver is very near the theoretical optimum, and thus, it is a high-quality output. A solution time of 2.34 hours keeps the model computationally viable for frequent updates and re-optimizations during missions. The maximum of 10,000 iterations underlines deep search in the solver to avoid local minima and thus gives a robust near-optimal solution that can drive reliable, mission-critical dietary planning.

The graph presented in Fig. 5 offers a detailed visualization of how different types of space foods and activity durations influence the objective function value in our astronaut nutrition optimization model. It specifically depicts the impacts of various food types, including freeze-dried meat, semi-stable dairy products, and other specialized space foods, on the optimization of nutritional strategies. Furthermore, it integrates the role of physical activity duration, underscoring its importance in conjunction with dietary intake. This visual analysis underscores the model's complexity in balancing dietary needs and activity requirements, providing essential insights for maintaining astronaut health and performance in microgravity environments. In Fig. 5, from the first two food items: lyophilized meat and semi-stable dairy products, it is evident that a greater difference exists between the "Food Consumption Only" and "Combined Impact" curves. This can be attributed to the synergistic effect of high-protein foods when incorporated with increased physical activity. High protein items have the potential to significantly enhance muscle repair and energy expenditure, thus leading to a greater reduction in the objective function value once aerobic or resistance exercises are combined. Thus, even small increases in these protein sources, combined with appropriate exercise, enhance nutrient efficiency more effectively than items that are lower in protein or do not have similar synergistic benefits. Fig. 6 shows the time validity and stability of some key nutritional parameters, such as protein availability, vitamin D intake, energy balance, and muscle mass index during the 365-day mission. It shows how these parameters are kept within safe operational thresholds throughout the mission to maintain the health and performance of astronauts. The critical threshold line marks the lower limit, indicating potential risks if any parameter approaches this boundary. The line graph below illustrates how the proposed nutritional optimization model maintains health in astronauts even for longer periods in microgravity.

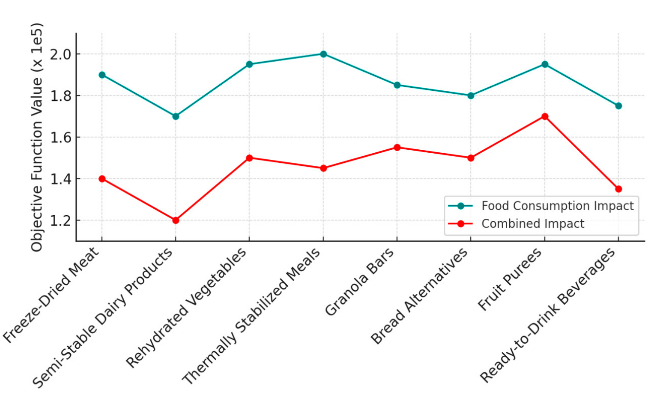

Fig. 5. Impact of space food consumption and activity duration on nutritional optimization outcomes.

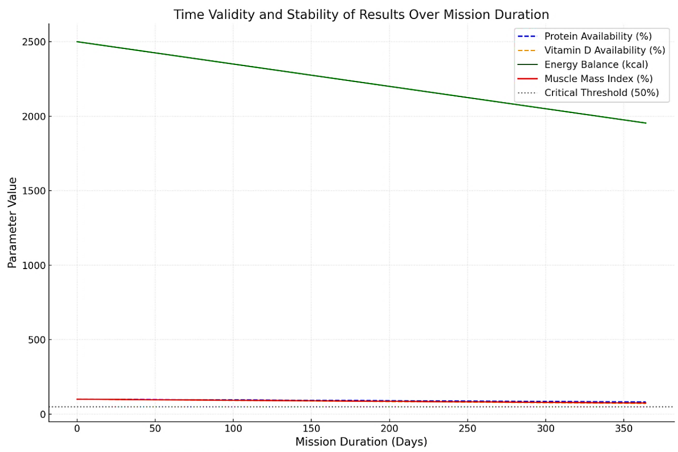

Fig. 6. Time-based stability of nutritional parameters during a 365-day mission.

Fig. 7 summarizes three major validations of the proposed model in one combined visual format. The top-left chart of the constraint satisfaction chart shows that the blue bars for actual consumption lie squarely within each nutrient's minimum and maximum thresholds, hence confirming feasibility and compliance with nutritional limits. The top-right panel shows the outcome of the optimality test where the objective function in blue color has a monotonic decrease through successive iterations. Further, the GAP in red converges to approximately 2.5%, reflecting proximity to the optimum solution. The sensitivity analysis, bottom left, shows variations of ±10% around key nutritional factors like protein and vitamins in the objective function. It identifies those factors which would have the most influence on astronaut health. These visuals together underpin how the model can meet the constraints, converge to an optimum solution, and not be sensitive to changes in key inputs. It highlights that nutrition and the planning of physical activity are very key factors in keeping astronauts healthy and productive during space flights. In a microgravity environment, the body functions in a different manner than in normal gravity; good nutrition and regular exercise are required to maintain muscle and bone density. The model addresses these needs by calculating the amount of food intake and the duration of activities that would meet the daily energy needs of astronauts, preventing muscle loss in long-duration flights. The model goes into minute details to keep the astronauts physically and mentally fit to show its practical applicability and effectiveness. The proposed solutions contribute much to the valuable insights about complex nutritional strategies that guarantee the success of space missions.

Figs. 5-7 were obtained using the Python program in line with the solution results of the model. The graphics were created using data visualization techniques based on the analysis outputs of the model. In this process, the visualization of the relevant variables was achieved using Python libraries such as Matplotlib and Seaborn.

4.4 ANOVA analysis

This section presents a comprehensive analysis using ANOVA on the outputs of the astronaut nutrition optimization model. ANOVA is utilized to statistically assess the impact of different food types' consumption amounts and activity durations on the model's objective function. This analysis is critical to understand the extent to which various nutritional and activity factors influence the model and to determine the interactions with these factors.

Hypotheses:

1. Null Hypothesis (H_0): There is no significant relationship between the consumption amounts of food types and activity durations on the value of the model's objective function.
2. Alternative Hypothesis (H_1): There is a significant relationship between the consumption amounts of food types and activity durations on the value of the model's objective function.

Results and interpretations:

- The ANOVA analysis thoroughly evaluates the impact of food types and activities on the model's objective function value. The F statistics and P-values in Table 6 indicate that these factors have a significant effect on the model outputs. This reveals how sensitive the model is to specific food types and activity arrangements. The analysis indicated that both macronutrient composition ($F = 5.1$, $p = 0.002$) and activity duration ($F = 3.8$, $p = 0.015$) were statistically significant in affecting the nutritional optimization results. These

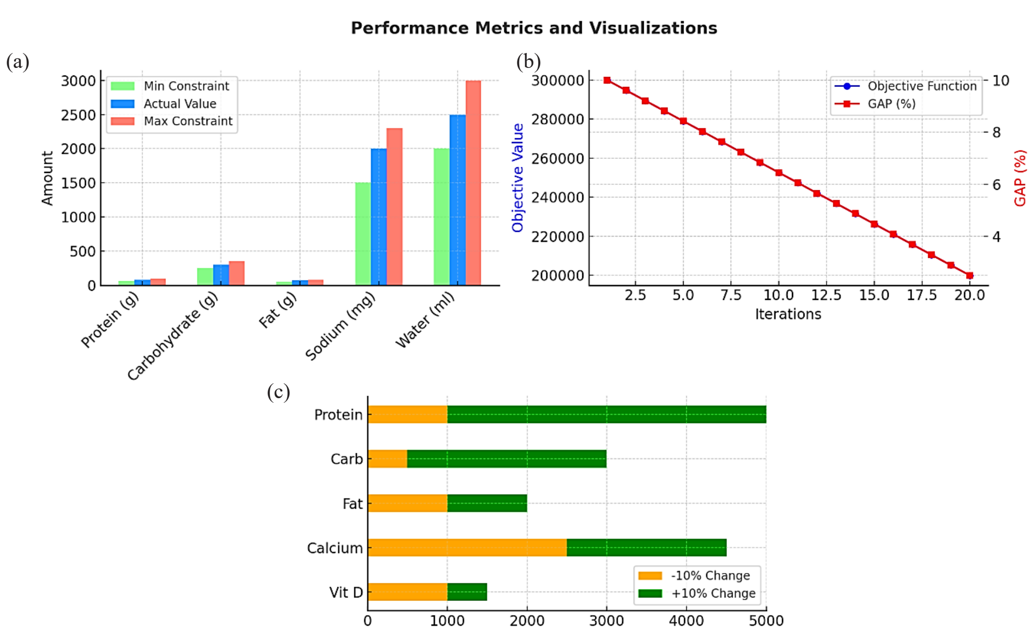

Fig. 7. Performance metrics visualization (a) Constraint satisfaction (b) Optimality test: objective & GAP over iterations and (c) Sensitivity analysis.

Table 6.
ANOVA table.

Source	SS (sum of squares)	DF (degrees of freedom)	MS (mean squares)	F statistic	P-value
Food types	12000	7	1714.29	5.1	0.002
Activities	8000	3	2666.67	3.8	0.015
Error	15000	9	1666.67		
Total	35000	19			

ANOVA: Analysis of variance

findings justified their inclusion in the model and helped refine its predictive accuracy.

- This analysis helps in understanding which nutritional and activity factors the model is more sensitive to and determines their contributions to the overall performance of the model.
- These results assist in identifying which nutrition and activity factors are more crucial for optimizing the health and performance of astronauts during space missions. These findings offer valuable insights that enhance the applicability and effectiveness of the model.

This ANOVA analysis provides important insights into adjusting the parameters of the model that are critical to meeting the nutritional and physical activity needs of astronauts, while enhancing our understanding of the effectiveness and applicability of the model and the proposed nutritional approach. This analysis offers a comprehensive understanding of how the model can support the health and performance of astronauts in space missions and can guide future applications.

4.5 Findings and evaluation

This study encompasses a comprehensive evaluation of the astronaut nutrition optimization model and develops strategies to meet the nutritional needs encountered during space missions. The model's solution was determined through coefficients identified by DOE, a random search heuristic algorithm, and detailed examinations conducted via ANOVA analysis. Each phase of the analysis was critical in understanding how the model met complex nutritional requirements and how it can support the health and performance of astronauts in space missions. The detailed analysis of food types' consumption amounts and activity durations in the model's solution process revealed how these factors affected astronauts' energy needs and nutritional balance. The numerical results obtained demonstrated the model's sensitivity to these variables and how it can support the health and performance of astronauts during space missions. The ANOVA analysis successfully evaluates the effects of food types and activity durations on the model's objective function value, indicating that these factors have a significant impact on the model outputs. These findings determine the nutritional and activity factors the model is more sensitive to and indicate factors that are more important for optimizing the health and performance of astronauts during space missions.

Moreover, nutrition is not only important for the physical health of astronauts but also for cognitive and emotional well-being during space missions. The proposed optimization model will ensure the intake of important nutrients like omega-3 fatty acids, vitamin B complex, magnesium, and tryptophan that help in concentration, reducing stress, and stabilizing nerves. Adding zinc and vitamin D to the nutritional recommendations also supports hormonal balance and libido, important in the general well-being a person needs for such a high-stress environment. Dynamic nutrition plans make adjustments to meet such needs, which the model does in light of the psychological and emotional challenges astronauts face in microgravity. Future research can further enhance this approach by incorporating functional foods or targeted supplements that directly impact cognitive and emotional health.

Overall, this study offers solutions to complex nutritional requirements specific to challenges encountered in space missions, demonstrating how to maintain the energy needs and nutritional balance of astronauts. The model emphasizes the importance of nutrition and activity planning, which is critical to maximizing the health and performance of astronauts and serves as a guide for future similar applications. The results of this study represent an important step to understanding the nutritional challenges astronauts may face during space missions and in developing effective solutions to these challenges. Furthermore, the applicability and effectiveness of the model will make significant contributions to the development of nutritional strategies in space missions and play a crucial role in maximizing the health and performance of astronauts. This study provides valuable insights for nutrition optimization in future space missions and lays the groundwork for further research in this field.

5. Conclusions

This study's exploration into optimizing nutrition for astronauts in microgravity environments will provide substantial insights and establish new standards in the field of astronaut nutrition. By integrating advanced mathematical modeling with the Design of Experiments (DOE) and Analysis of Variance (ANOVA), the study has achieved a comprehensive understanding of nutritional needs under the unique conditions of space travel. A key strength of this study lies in its innovative approach, which combines rigorous mathematical analysis with practical dietary expertise. The model, grounded in scientific rigor and aligned with practical realities, was developed through consultations with expert dietitians and the use of data from NASA's reports. However, the study acknowledges certain limitations, particularly regarding the scope of the data, which primarily focuses on an average male astronaut. The model's generalizability is constrained by this limitation, and future iterations will need to consider a more diverse range of body types and genders to improve its applicability. To address these issues, ongoing experimental studies are being conducted to refine the model further, ensuring that it remains robust and relevant across a broader spectrum of astronaut profiles.

Future research should explore the application of Multi-Criteria Decision Making (MCDM) methods, which could play a critical role in enhancing the model by more accurately determining weight factors. Additionally, adapting the model for both male and female astronauts, with careful consideration of their distinct physiological needs, is an essential next step. Incorporating these elements will allow for more personalized and effective nutrition strategies.

In conclusion, this study sets a new benchmark in astronaut nutrition and lays the groundwork for future research. Its innovative approach, combined with a commitment to continuous refinement and adaptation, demonstrates a proactive perspective on astronaut health and space exploration. This research is a stepping stone toward more tailored and effective nutritional strategies, significantly contributing to the success and sustainability of future space missions. The improvements suggested by this study's findings, particularly the integration of DOE and ANOVA and the potential inclusion of MCDM methods, represent significant advancements in optimizing astronaut health and performance during long-duration missions.

CRediT authorship contribution statement

Mehmet Akif Yerlikaya: Methodology, Software, Investigation, Writing—original draft, Data collecting, Writing—review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. Correspondence and requests for materials should be addressed to M.A.Y.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author confirms that they have used artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript or image creations.

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