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A systematic literature review on dietary intake and nutrition-related adaptations across isolation and confinement

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Maintaining adequate nutritional intake and body mass is critical in spaceflight and its terrestrial analogs; however, comprehensive evidence on dietary intake patterns and nutritional adaptations during long-term isolation and confinement remains limited. Following PRISMA guidelines, this systematic review synthesizes evidence on dietary intake and nutrition-related adaptations in isolated and confined environments. Across 184 studies, dietary structure ranged from highly standardized to highly variable. Energy intake differed substantially across habitats, whereas macronutrient distributions remained within recommended ranges, characterized by stable protein intake across habitats and more variable carbohydrate and fat contributions. Body mass generally decreased, with the greatest heterogeneity observed in terrestrial isolated, confined, and extreme environments. Vitamin D insufficiency was consistently reported but could be effectively prevented through supplementation. Overall, isolated and confined environments challenge nutritionally adequate food systems, and current evidence is insufficient to draw firm conclusions on optimal strategies, particularly for longer-duration space missions.

Long-duration exposure to isolated and confined environments, including isolated, confined, and extreme (ICE) and isolated, confined, and controlled (ICC) settings, places substantial physiological and behavioral demands on humans[1]. These environments, which include space missions and terrestrial space analogs, are defined by prolonged isolation, constrained autonomy, limited food systems, and restricted resupply. Under such conditions, sustaining adequate energy intake to preserve energy balance, body mass, and body composition constitutes a central challenge for health and operational performance[2–5].

Alterations in energy intake and associated changes in body mass have been reported in spaceflight[6–13] as well as in terrestrial isolated and confined environments[14–17]. However, it remains unclear whether these changes are consistent in direction, comparable in magnitude, or reproducible across different studies and operational contexts. Observed differences across habitats may reflect contextual factors, including environmental stressors, physical workload, operational constraints, and the degree of dietary control. In addition, alterations in appetite regulation[4,5], sensory perception[18,19], psychological stress[1], circadian disruption[20], motion sickness, particularly during early phases of spaceflight[5,6], and limitations in food availability[21,22] or dietary variety[23,24] may contribute to changes in energy intake under such conditions.

One key structural dimension underlying these differences is food system design, which varies across isolated and confined settings. Spaceflight missions and bed-rest studies are typically characterized by a high degree of dietary standardization, including predefined nutritional targets and a restricted food environment that limits individual food choice[4,5,25]. In contrast, terrestrial ICE environments, such as Antarctic research stations, operate under more variable logistical and environmental constraints that may influence food availability and selection, often resulting in largely self-selected, ad libitum intake[22,26]. ICC environments, such as MARS500 and Human Exploration Research Analog (HERA), are commonly designed to combine elements of experimental control with selected operational constraints. Taken together, these contextual differences provide an important

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framework for interpreting reported patterns of energy intake and body mass changes across isolated and confined settings.

Beyond total energy intake, macronutrient distribution plays an important role in maintaining physiological stability and supporting adaptive capacity in isolated, confined, and operationally constrained environments[5]. The relative contributions of carbohydrates, fats, and proteins influence key metabolic and functional processes, including substrate utilization, muscle maintenance, immune function, and recovery from physical and psychological stress[27]. While macronutrient targets for spaceflight[4,5] are partly based on World Health Organization (WHO) recommendations (10%–15% protein, 20%–35% fat, and 45%–60% carbohydrates[5,6,28,29]), systematic evidence assessing alignment with reported dietary intake and enabling comparisons of dietary intake patterns across isolated and confined environments, particularly regarding the comparability of terrestrial ICE and ICC space analogs with actual spaceflight missions, remains limited.

Nutritional adequacy in isolated and confined environments extends beyond energy and macronutrient composition. Micronutrient status represents an additional dimension of nutritional vulnerability, particularly under conditions of limited dietary diversity, restricted access to fresh foods[24], and prolonged reliance on shelf-stable food systems. Environmental factors such as reduced ultraviolet exposure, circadian disruption, and physiological stress may further constrain micronutrient intake and metabolism[30–32], potentially resulting in setting-specific micronutrient inadequacies. Micronutrients with strong environmental dependencies may therefore be particularly affected in isolated and confined environments. Vitamin D warrants specific consideration due to its limited availability from dietary sources and the lack of endogenous synthesis in the absence of ultraviolet light[14,30,33], as well as its roles in calcium homeostasis and bone metabolism and broader extraskeletal effects in other physiological systems[5,34]. Other micronutrients may also be relevant in isolated and confined settings; however, the available evidence is too limited to support robust, environment-specific intake or supplement recommendations across different isolated and confined environments.

The available literature on nutrition in isolated and confined environments comprises a diverse set of study designs and settings; however, systematic evidence synthesizing nutritional outcomes across ICE and ICC environments remains limited. Small sample sizes and methodological heterogeneity further challenge comparability and transferability across habitats. The aim of this systematic review is to examine nutritional intake and related adaptations across different ICE and ICC environments within their respective operational contexts. Dietary provision and intake patterns are therefore compared across habitat types, with changes in body mass considered as a contextual indicator of the adequacy of reported energy intake. Where available, micronutrient intake and status are additionally examined to provide complementary insight into nutritional adequacy across settings. By synthesizing similarities and differences in nutritional intake patterns across diverse isolated and confined environments, this review aims to evaluate the extent to which dietary intake is comparable across habitats and to identify common nutritional considerations as well as context-specific factors that may influence nutritional adequacy under constrained conditions.

Methods

Databases and search strategy

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[35]. Studies examining nutritional intake and diet-related outcomes in ICE environments were identified through searches of PubMed, Web of Science, and the Cochrane Library (Wiley), performed in August 2022. An updated literature search was performed in December 2025 to identify newly published studies. The review protocol was prospectively registered in PROSPERO (CRD42023480161). The complete search strategy was developed in collaboration with a specialist research librarian and is provided in Supplementary Text S1. It comprises three conceptual modules: ICE conditions, human nutrition, and exclusion of animal studies. A high-specificity set of search terms was applied to identify studies conducted under isolation and confinement conditions, based on terminology validated in previous systematic reviews[36,37]. To complement database searches and enhance retrieval across heterogeneous isolation analogs, a targeted hand search was performed using a semantic search approach[38]. This strategy was used to identify relevant studies that may not be consistently indexed under standard subject headings or that employ non-standard terminology to describe isolation or confinement settings.

Eligibility criteria

Inclusion criteria were based on the five PICOS dimensions, i.e., participants, intervention, comparator, outcome, and study design[39].

Population. Healthy adult participants (≥18 years), regardless of sex, age, or body weight, who had been exposed to isolated and confined environments for a minimum duration of four weeks (28 days). A minimum confinement duration of 28 days was selected to focus on sustained rather than acute exposure, as shorter isolation periods may be less informative for longer-term adaptations. Studies involving clinical populations or animal models were excluded.

Intervention. Residency in ICE or ICC environments is characterized by restricted access to fresh foods, complex food logistics, and prolonged reliance on shelf-stable food systems. Eligible settings included spaceflight missions; terrestrial space analogs such as MARS-500, HERA, SIRIUS, and Lunar Palace-1; head-down bed-rest studies inducing microgravity-like physiological adaptations; and expeditions in remote regions, including Antarctica, the Arctic, and Siberia.

Comparison. The presence of a control group was not required. Studies employing within-subject comparisons (e.g., baseline vs. confinement) or between-group comparisons were eligible.

Outcome. Primary outcomes comprised total energy intake (kcal/day), macronutrient intake (E% or g/day), micronutrient intake, and reported dietary intake patterns or nutritional strategies. Secondary outcomes included anthropometric measures (e.g., body mass) and additional nutrition-related parameters, such as blood or urine biomarkers, appetite ratings, and psychological factors related to food intake or nutrient demands.

Study design. Both observational and interventional studies were eligible. Reviews, conference abstracts, and non-human studies were excluded.

Only original research articles were included, with no restrictions on publication date or language.

Screening and literature organization

Search results from all databases were combined, and duplicate records were removed prior to screening. Titles and abstracts were independently screened by three reviewers (B.K., D.R., E.D.) to assess potential eligibility. Full-text articles were subsequently evaluated for inclusion. Any disagreements were resolved through discussion among the reviewers, with unresolved cases adjudicated by a fourth author (I.M.).

To facilitate structured synthesis and to account for contextual heterogeneity, included studies were categorized according to the type of isolated and confined environment in which they were conducted. The following habitat groups were defined a priori:

1. Space missions
2. Terrestrial space analogs, further subdivided into:
   a. Terrestrial ICE environments (e.g., polar research stations)
   b. Terrestrial ICC studies (e.g., long-duration confinement experiments, closed ecological systems)

c. Terrestrial ICC studies reflecting microgravity-like physiological adaptations (e.g., head-down bed-rest models)

Data items and statistics

Data extracted from each included study comprised study characteristics, isolation or confinement conditions, participant characteristics (age, sex, and weight status, including body weight [kg] and/or BMI [kg/m²]), and all available information on dietary intake and nutritional status. Although sex was extracted where reported, sex-specific analyses were not feasible due to limited sex-disaggregated reporting. Study characteristics were extracted as reported in the original publications and summarized in tabular format.

Primary outcomes focused on dietary intake parameters, including total energy intake (kcal/day), macronutrient and micronutrient intake (expressed as E%, g/day, mg/day, or µg/day, as appropriate), and reported dietary strategies such as food and fluid types, meal frequency, supplement use, self-selected versus controlled feeding, and adherence to standardized menus. Secondary outcomes included body mass changes and trajectories, biochemical markers of nutritional status, additional body composition measures, physiological, appetite-related, and psychological parameters. Control groups without exposure to isolation or confinement were not included in subsequent analyses.

To avoid double-counting of participant cohorts, overlapping mission- or habitat-based reports were consolidated when overlap was explicitly stated or could be reliably inferred from participant characteristics (e.g., sex, age, crew size), study period, or methodological details. When overlap could neither be clearly confirmed nor excluded, studies were retained and analyzed separately to avoid unwarranted assumptions or data exclusion. Studies reporting outcomes from more than one habitat type were assigned to each relevant group and flagged accordingly.

For quantitative analyses, duplicate outcome reports referring to the same mission or participant cohort were consolidated, and mean values were used to derive Δ-values where applicable. When study durations were reported as ranges for aggregated mission datasets and could not be further resolved, the midpoint of the reported range was used as a standardized duration. To ensure consistency, fixed conversion factors were applied (1 month = 30 days; 1 year = 12 × 30 days). Pre–post outcomes were derived using the closest available measurements to the defined start and end of isolation, confinement, or mission duration.

Incomplete or inconsistent reporting across studies, including unclear sample sizes, missing micronutrient data, non-harmonized measurement time points, or heterogeneous outcome units, was documented. With the exception of unit standardization, no further data imputation or harmonization was performed in order to preserve the integrity of the original data.

Graphical visualizations were generated using R[40], Microsoft Excel, and *robvis*[41].

Risk of bias assessment

The assessment of bias for the included studies was conducted using the Risk of Bias in Non-randomized Studies of Interventions (ROBINS-I) tool[42]. In accordance with the ROBINS-I framework, each study was evaluated as an attempt to emulate a hypothetical pragmatic randomized trial and assessed across seven domains of potential bias. These domains address bias due to confounding and participant selection prior to intervention ("baseline"), bias in the classification of interventions, and bias arising after intervention initiation, including deviations from intended interventions, missing data, measurement of outcomes, and selection of the reported result. Overall risk of bias judgments range from low to moderate, serious, or critical risk.

Results

Of the 1797 identified studies, 184 met the criteria for qualitative analysis (Fig. 1), including 34 studies in Group 1 (space missions), 69 in Group 2a (space analogs: terrestrial ICE environments), 35 in Group 2b (space analogs: terrestrial ICC environments), and 48 in Group 2c (space analogs: terrestrial ICC studies reflecting microgravity-like physiological adaptations). Two studies[43,44] reported outcomes across multiple habitat categories and were therefore included in more than one group.

Study characteristics

A detailed overview of the characteristics across the studies is provided in Table 1 and for the single trials in Table 2. The characteristics across the studies are summarized in the text.

The 184 included studies were published between 1957 and 2025. Most originated from European research groups (46.2%), followed by studies from the United States (33.2%) and Asia (7.6%). A smaller proportion of studies was conducted by researchers from Australia/Oceania (6.0%) and South America (0.5%), while 7.1% represented intercontinental collaborations.

Several publications reported data from identical or overlapping participant cohorts. In spaceflight research, this included repeated reporting from the Skylab 2-4 crews[43,45–51], the Soviet/Russian Salyut and MIR missions[44,52–69], European MIR missions[66,70], and International Space Station (ISS) expeditions[30,71–73]. Similar patterns were observed in polar research, where multiple articles described the same polar expeditions[74,75], or Antarctic overwintering crews from American[76,77], Australian[78,79], Indian[80,81], and Israeli research teams[82,83]. Additional duplication was identified in major isolation and bed-rest programs, including BIOS-2[15,84–86], Mars-105[87–89], Mars-500[90,91], EXEMSI[92–94], other chamber simulations[44,95–97], and several 6° head-down bed-rest studies, and several 6° head-down bed-rest campaigns conducted within the MEDES framework[98–104], including the ESA-WISE study[28,105–114]. Further repeated reporting was observed in studies by Bychkov et al.[115–117], Greenleaf et al.[118,119], and Ritz et al.[120,121].

Across all included studies, 2935 participants were reported; however, incomplete reporting of participant overlap between studies prevents a precise determination of the number of unique individuals. Most studies included male-only samples (65%), followed by mixed-sex cohorts (26%), while participant sex was not reported in 6% of studies. Reported participant ages ranged from 18 to 63 years, and durations of isolation or confinement varied from 28 days to 2 years. Dietary assessment methods differed across habitat types. Spaceflight studies predominantly employed standardized, pre-defined rations or weighed food records. Terrestrial ICE studies mainly used weighed food records, whereas terrestrial ICC environments relied on questionnaires and/or weighed food records. ICC studies reflecting microgravity-like physiological adaptations, exclusively based on head-down bed-rest protocols, applied fully controlled dietary regimens.

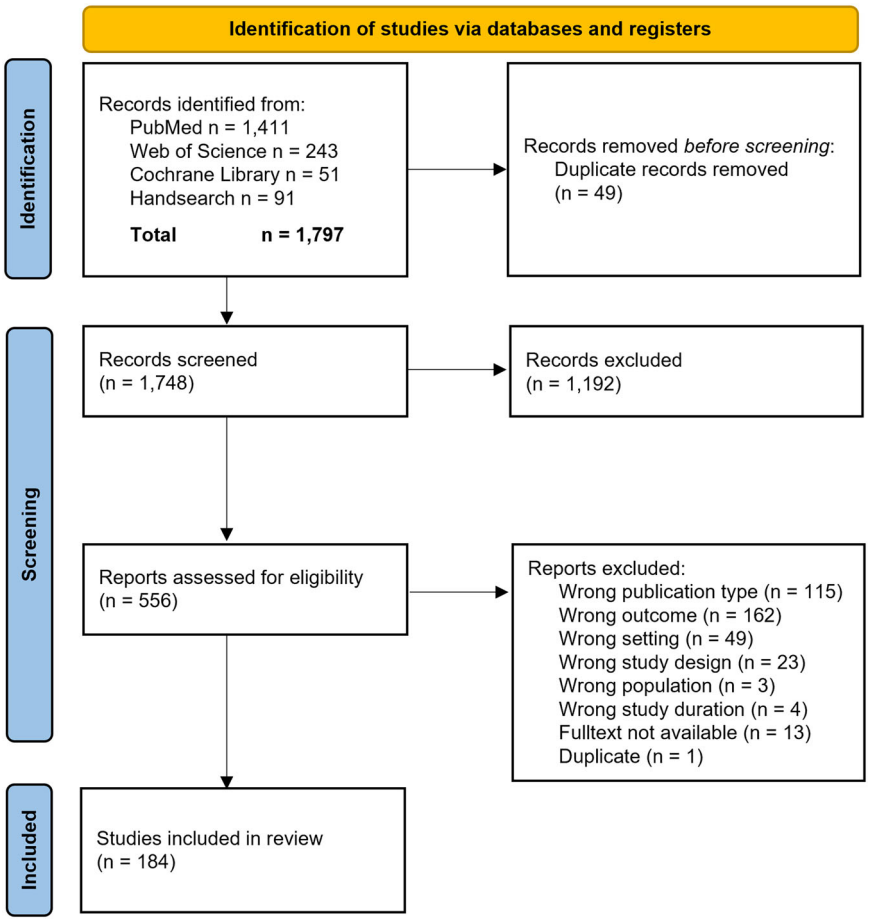
Study outcomes

The study outcomes are summarized in the main text and presented in greater detail in Table 2 and Supplementary Table S1-3 (S1: Quantitative body mass changes; S2: nutrition-dependent biomarkers; S3: further anthropometric, vital, psychological/subjective, and performance-related outcomes).

Habitat-specific dietary structures varied, reflecting differences in dietary control, food availability, and reliance on preserved foods

Spaceflight. Dietary provision during spaceflight was predominantly standardized and organized into repetitive, multi-day menu cycles, largely based on thermostabilized, freeze-dried, dehydrated, and canned foods, with three to four meals per day. Earlier programs such as Skylab operated with approximately 70 food items on a six-day rotating menu; subsequent missions, including ISS, expanded both food inventory and menu cycle length, though individual food choice remained constrained relative to free-living conditions (Table 2). In some missions, this standard menu was supplemented by additional, crew-specific foods supplied via individual preference containers. Menus typically included shelf-stable meat products, cereals, dairy items, vegetables, fruits, soups, confectionery, and beverages, whereas access to fresh foods was generally limited and restricted to short periods following resupply missions. In some missions, specific dietary interventions were implemented, such as

Fig. 1 | PRISMA flowchart.



sodium-restricted diets or modified rations aimed at stabilizing appetite or metabolic responses, to examine the effects of targeted nutritional adjustments under flight conditions. Metabolic balance studies conducted during missions such as Skylab and on the ISS relied on tightly controlled diets with fixed nutrient compositions, whereas a smaller number of missions permitted ad libitum intake within the constraints of the available onboard food inventory[59,67]. Overall, dietary practices during spaceflight were shaped by a high degree of menu standardization, limited availability of fresh foods, and a reliance on shelf-stable food technologies to support nutritional adequacy under microgravity conditions.

Terrestrial ICE environments. Dietary provision in terrestrial ICE environments predominantly relied on shelf-stable, frozen, canned, and dehydrated foods, reflecting infrequent resupply and severe environmental constraints. In contrast to spaceflight food systems, most terrestrial ICE stations have access to cold storage, which may support comparatively greater dietary variety and food quality. However, prolonged storage and transport conditions can reduce the usability and nutritional value of fresh produce over time, and access to fresh fruits and vegetables was generally limited to short periods following summer resupply and often absent during winter-over phases.

At Antarctic research stations, food provision was commonly organized and partly standardized, frequently involving professional catering services offering mixed Western or national cuisines within regular meal schedules. However, the degree of dietary autonomy varied considerably across stations. While some settings allowed largely self-selected, ad libitum intake from bulk-shipped frozen, canned, and dehydrated foods, others implemented fixed menus or provided identical diets to all participants.

In contrast, outdoor operations such as skiing, sledging, or extended field expeditions required prepackaged, energy-dense rations designed to support thermoregulation and meet the substantially increased physical demands associated with prolonged cold exposure and endurance activity. These rations offered little dietary choice, and intake was described as flexible; however, detailed quantitative intake data were infrequently reported.

Nutritional interventions in terrestrial ICE settings included low-fat or high-fiber dietary regimens, canola-based fat substitutions, and variable vitamin D supplementation strategies, reflecting both research objectives and operational requirements. Alcohol policies also differed across settings, ranging from ad libitum access during social occasions at stations to strict prohibition during field operations.

Overall, dietary practices in terrestrial ICE environments encompassed a broad spectrum, ranging from flexible, ad libitum station-based meals to highly regimented expedition rations. This variability was shaped by geographic isolation, seasonal resupply constraints, national program practices, and logistical considerations.

Terrestrial ICC environments. Dietary provision in ICC environments was generally highly structured and protocol-driven. Diets were frequently modeled on spaceflight food systems and relied predominantly on shelf-stable, dehydrated, freeze-dried, or thermostabilized foods, while physical activity levels were often constrained by experimental or operational conditions. Nutrient adequacy was typically addressed through predefined menu planning aligned with WHO or ISS reference standards, resulting in tightly specified macronutrient and micronutrient compositions.

In operational ICC settings, such as submarines, access to fresh foods was usually limited to the initial phase of deployment. As missions progressed, crews increasingly depended on stored and processed foods, which were commonly associated with reduced intake of fruits, vegetables, and

Table 1 | Study characteristics across the studies

	Group 1: space missions	Group 2a: terrestrial ICE environments	Group 2b: terrestrial ICC environments	Group 2c: terrestrial ICC studies reflecting microgravity-like physiological adaptations
Total studies (*n*)	34	69	35	48
Participants				
Total	~238	~1859	401	437
Median [IQR]	9 [16]	N.R.	8 [16]	14 [10]
Range	1–44	1–225	3–58	6–37
Not reported (*n* studies)	0	3	0	0
Sex (f%)				
Range	0–50	0–100	0–50	0–100
Not reported (*n* studies)	2	4	0	2
Age (years)				
Range	33–50	21–63	18–52	18–50
Not reported (*n* studies)	12	7	2	2
Weight (kg)				
Range	72–85.6	50.0–95.6	65.8–96.0	55.3–82.0
Not reported (*n* studies)	12	17	8	4
Isolation length				
Median [IQR]	N.R.	N.R.	64 days [65 days]	60 days [43 days]
Range	28 days–438 days	29 days–2 years	28 days–2 years	28 days–182 days
Not reported (n studies)	1	1	0	0

Summary of study and participant characteristics across the four habitat groups. Reported variables include the number of studies and participants, sample size distribution (median, interquartile range (IQR), range), sex, age, body weight, and isolation duration. *n* refers to the number of studies, as specified. *ICE* isolated, confined and extreme, *ICC* isolated, confined and controlled, *N.R.* not reported.

dietary fiber. Consumption of alcohol and caffeine varied in accordance with mission-specific operational policies.

In controlled isolation studies, including long-duration confinement experiments such as Mars-500 and metabolic chamber studies, dietary intake was subject to even stricter regulation. These protocols typically involved prescribed menus, fixed portion sizes, and monitoring of intake to ensure protocol adherence. Dietary manipulations included sodium-restricted regimens, flavonoid-enriched diets, controlled omnivorous menus, and plant-based systems incorporating on-site food production (e.g., Biosphere 2).

Overall, dietary practices across ICC environments ranged from highly regulated laboratory-based protocols to operationally constrained submarine food systems. Despite this variability, ICC diets were consistently characterized by a reliance on preserved foods and limited availability of fresh produce, with differences largely determined by mission context and the degree of dietary control.

Terrestrial ICC studies reflecting microgravity-like physiological adaptations. Dietary provision during bed-rest studies was highly standardized and frequently designed to be isocaloric, while physical activity was concurrently restricted to strict recumbency. Meals were typically organized into fixed menu cycles of 7–20 days, providing three main meals and one to two snacks per day.

Energy intake was calibrated to maintain body mass or to meet predefined metabolic targets, primarily based on resting metabolic rate assessed by indirect calorimetry. When direct measurements were unavailable, resting energy expenditure was estimated using the Harris–Benedict equations and adjusted for activity level[122–125]. Macronutrient distributions commonly ranged from approximately 50–60% carbohydrates, 25–35% fat, and 12–20% protein. In most protocols, complete consumption of all provided food items was required, and actual intake was monitored using weighed food portions or digital tracking systems. Diets were prepared in hospital or metabolic kitchen facilities under strict control of nutrient composition, although limited plate waste was permitted in some protocols. To minimize metabolic confounding, alcohol, caffeine, chocolate, dietary supplements, and additional foods were commonly restricted.

Nutritional interventions in bed-rest studies included high-protein regimens aimed at attenuating muscle loss, branched-chain amino acid (BCAA) supplementation to support protein synthesis, antioxidant protocols to mitigate oxidative stress, and sodium or iodine manipulations to examine fluid–electrolyte balance and endocrine regulation. These dietary strategies were frequently evaluated alongside exercise-based countermeasures, such as resistance training or lower body negative pressure (LBNP) treadmill exercise, which targeted musculoskeletal deconditioning during prolonged unloading.

All environments. Dietary control differed systematically across habitat types. Spaceflight and bed-rest studies were characterized by the highest degree of dietary standardization, including predefined energy and macronutrient targets, fixed menu cycles, and minimal opportunities for self-selection. Diets were centrally prepared, either as engineered, shelf-stable space foods or as tightly controlled metabolic-kitchen menus.

In contrast, terrestrial ICE environments exhibited the greatest heterogeneity. Dietary targets were not consistently predefined or individualized across studies, and food availability was strongly influenced by resupply logistics and operational context. Station-based meals ranged from structured menus prepared by professional cooks to largely self-selected, ad libitum intake. Outdoor expeditions typically relied on prepackaged, high–energy-density rations designed to meet the increased demands of

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Table 2 | Overview of single study characteristics

Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
1	Agureev et al.[63]	RUS	MIR orbital station (22 missions)	–	N.R.	>20	0	N.R.	N.R.	N.R.	Standardized pre-defined rations
2	Agureev et al.[71]	RUS	ISS	Mission 1	141 d	3	0	N.R.	77.3 ± 6.9	N.R.	Standardized pre-defined rations
			ISS	Mission 2–7	129–196 d	17	12	N.R.	75.0 ± 8.0	N.R.	
3	Bychko et al.[54]	USSR	Salyut-6 orbital station	–	75–185 d	10	0	N.R.	79.5 ± 5.7	N.R.	Standardized pre-defined rations
4	Bychkov et al.[55]	USSR	Salyut-7 orbital station	–	126–237 d	12	0	N.R.	74.3 ± 3.5	N.R.	Standardized pre-defined rations
5	Drummer et al.[70]	GER, NLD	MIR orbital station	EuroMIR94	30 d	2	0	50.0 ± 3.0	74.5 ± 2.5	N.R.	Barcode-based intake tracking
6	Frings-Meuthen et al.[72]	GER	ISS	–	62–196 d	8	0	50.0 ± 2.8	85.6 ± 8.9	N.R.	Controlled metabolic diet with 24-h urinary sodium
7	Garrett-Bakelman et al.[129]	USA	ISS	–	340 d	1	0	50	N.R.	N.R.	N.R.
8	Gazenko et al.[52]	USSR	Salyut-4 orbital station	–	30 d	2	0	N.R.	N.R.	N.R.	N.R.
9	Gazenko et al.[53]	USSR	Salyut-7 orbital station	–	237 d	3	0	37.7 ± 3.3	73.0–79.0	N.R.	N.R.
10	Grigor'ev et al.[56]	USSR	Salyut-6 orbital station	–	185 d	2	0	38.0 ± 3.0	N.R.	N.R.	N.R.
11	Grigor'ev et al.[58]	USSR	Salyut-7 orbital station	–	237 d	3	0	N.R.	N.R.	N.R.	N.R.
12	Grigoriev and Noskov[64]	RUS	MIR orbital station (EO 5, 7, 8, 9, 10, 13, LD3)	–	132–312 d	11	N.R.	N.R.	N.R.	N.R.	N.R.
13	Grigoriev et al.[57]	USSR	MIR orbital station (EO 3)	–	366 d	2	0	38.0 ± 2.0	79.5 ± 0.5	25.7 ± 0.1	N.R.
14	Grigoriev et al.[65]	RUS	MIR orbital station (EO-2–8)	–	130–366 d	18	0	42.9 ± 5.3	N.R.	N.R.	N.R.
15	Heer et al.[66]	GER	MIR orbital station	EuroMIR94	29 d	2	0	50.0 ± 3.0	75.5 ± 2.0	N.R.	Barcode-based intake tracking with chemically analyzed space-food
			MIR orbital station	EuroMIR95	179 d	2	50	36.5 ± 0.5	72.0 ± 4.8	N.R.	
16	Larina[69]	RUS	Salyut-4,6,7 and MIR orbital stations	–	30–438 d	44	0	N.R.	N.R.	N.R.	Fluid and electrolyte intake recorded on metabolic days
17	Leach and Rambaut[45]	USA	Skylab 2	–	28 d	3	0	N.R.	N.R.	N.R.	N.R.
18	Leach and Rambaut[46]	USA	Skylab 2	Skylab 2	28 d	9	0	N.R.	N.R.	N.R.	Standardized, chemically analyzed diet
			Skylab 3	Skylab 3	59 d	6	0	N.R.	N.R.	N.R.	
			Skylab 4	Skylab 4	84 d	3	0	N.R.	N.R.	N.R.	
19	Leach et al.[47]	USA	Skylab 2	Skylab 2	28 d	9	0	N.R.	N.R.	N.R.	N.R.
			Skylab 3	Skylab 3	59 d	6	0	N.R.	N.R.	N.R.	
			Skylab 4	Skylab 4	84 d	3	0	N.R.	N.R.	N.R.	
20	Oganov et al.[68]	RUS	Salyut, MIR orbital station	–	1–14 m	38	N.R.	33–53	N.R.	N.R.	N.R.
21	Rambaut and Johnston[48]	USA	Skylab 2	Skylab 2	28 d	9	0	N.R.	N.R.	N.R.	Weighed food records
			Skylab 3	Skylab 3	59 d	6	0	N.R.	N.R.	N.R.	
			Skylab 4	Skylab 4	84 d	3	0	N.R.	N.R.	N.R.	

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Table 2 (continued) | Overview of single study characteristics

Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
22	Rambaut et al.[50]	USA	Skylab 2	Skylab 2	28 d	9	0	N.R.	N.R.	N.R.	Weighed food records
			Skylab 3	Skylab 3	59 d	6	0	N.R.	N.R.	N.R.	
			Skylab 4	Skylab 4	84 d	3	0	N.R.	N.R.	N.R.	
23	Rambaut et al.[49]	USA	Skylab 4	–	84 d	3	0	N.R.	N.R.	N.R.	Weighed food records
24	Smith et al.[51]	USA	Skylab 2	Skylab 2	28 d	3	0	N.R.	N.R.	N.R.	Standardized, chemically analyzed diet
			Skylab 3	Skylab 3	59 d	3	0	N.R.	N.R.	N.R.	
			Skylab 4	Skylab 4	84 d	3	0	N.R.	N.R.	N.R.	
25	Smith et al.[1,44]	USA	MIR Orbital Station	–	4 m	2	0	47.0 ± 9.9	79.6 ± 18.1	N.R.	Weekly computerized FFQ with telemetry transmission to NASA
26	Smith et al.[30]	USA	ISS (Mission 1–8)	–	128–195 d	11	18	46.5 ± 4.1	75.4 ± 6.2	N.R.	Weekly computerized FFQ with telemetry transmission to NASA
27	Smith et al.[73]	USA	ISS (Mission 14–20)	Interim Exercise	160 ± 62 d	8	33	45.0 ± 3.9	79.0 ± 12.0	N.R.	Weekly computerized FFQ with telemetry transmission to NASA
				Advanced Exercise	134 ± 61 d	5	40	46.6 ± 2.0	74.0 ± 13.0	N.R.	
28	Stein et al.[67]	USA, RUS	MIR Orbital Station		88–186 d	6	17	N.R.	81.9 ± 5.3	N.R.	Barcode-based intake tracking
29	Thornton and Ord[2,43]	USA	Skylab 2	Skylab 2	28 d	3	0	N.R.	N.R.	N.R.	Weighed food records
			Skylab 3	Skylab 3	59 d	3	0	N.R.	N.R.	N.R.	
30	Vorob'ev et al.[59]	USSR	Salyut-4 orbital station	–	63 d	2	0	44	N.R.	N.R.	Standardized pre-defined rations
31	Vorob'ev et al.[60]	RUS	Salyut-6 orbital station	–	96–140 d	4	N.R.	N.R.	N.R.	N.R.	Standardized pre-defined rations
32	Vorob'ev et al.[61]	RUS	Salyut-6 orbital station	–	75–185 d	10	N.R.	N.R.	N.R.	N.R.	Standardized pre-defined rations
33	Vorobyov et al.[62]	USSR	Salyut-4 orbital station	30 d-mission	30 d	2	0	N.R.	N.R.	N.R.	Standardized pre-defined rations
				63 d-mission	63 d	2	0	N.R.	N.R.	N.R.	
34	Zwart et al.[173]	USA	ISS	High Protein/K$^+$	160 ± 20 d	17	24	47.0 ± 6.0	N.R.	24.6 ± 3.0	Controlled weighed spaceflight diet
				Low Protein/K$^+$							
Group 2a: terrestrial ICE environments											
35	Acheson et al.[68]	UK	Halley Bay, Antarctica	–	1 y	12	0	24.0 ± 2.4	71.6 ± 8.1	22.3 ± 1.9	Weighed food records, 24-h dietary recalls, 24-h duplicate samples calorimetry
36	Adams et al.[174]	USA	Little America V, Antarctica	–	8 m	11	0	N.R.	N.R.	N.R.	N.R.
37	Anton-Solanas[175]	UK	South pole expedition, Antarctica	–	29 d	1	0	36	94.5	26.7	Self-supported field diet with pre-packed daily rations (no resupply)
38	Antonis et al.[176]	UK	Halley Bay, Antarctica	Halley Bay	1 y	24	0	25	74	23.1	24-h Weighed food records; sledging rations weighed pre/post
			SANAE Station, Antarctica	SANAE Station	1 y	10	0				
39	Belkin and Karasik[82]	ISR	Mirny Station, Antarctica	–	10 m	66	0	38.5 ± 8.4	78.2 ± 9.6	26.0 ± 2.9	Standardized food rations
40	Belkin and Karasik[83]	ISR	Mirny Station, Antarctica	–	10 m	66	0	38.5 ± 8.4	78.2 ± 9.6	26.0 ± 2.9	Standardized food rations
41	Bhatia and Pal[177]	IND	Maitiri Station, Antarctica	–	12 m	26	0	43.7 ± 9.4	74.4 ± 11.1	26.2 ± 3.0	N.R.

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Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
42	Bhushan et al.[178]	IND	Maitiri Station, Antarctica	–	4 m	11	0	22–60	N.R.	N.R.	N.R.
43	Bittel[179]	FRA	Ski expedition, Arctica	–	63 d	1	0	N.R.	N.R.	N.R.	Pre-packed food rations
44	Boyd[180]	AUS	Davis Station, Antarctica	–	42 d	3	0	29.7 ± 6.7	76.0 ± 11.1	N.R.	N.R.
45	Caputo et al.[181]	ITA	Concordia Station, Antarctica	–	12 m	13	23	34.1 ± 3.1	N.R.	N.R.	N.R.
46	Case et al.[182]	USA	McMurdo Station, Antarctica	–	12 m	7	14	33.8 ± 3.4	86.9 ± 9.1	25.6 ± 1.8	N.R.
47	Chen et al.[183]	CHN	Great Wall Station, Antarctica	Great Wall Station	13 m	12	0	40.3 ± 10.0	75.8 ± 8.9	25.4 ± 1.9	N.R.
			Zhongshan Station, Antarctica	Zhongshan Station	13 m	16	0	33.9 ± 10.4	72.6 ± 8.1	24.1 ± 2.7	
48	Choi et al.[184]	KOR	King Sejong Station, Antarctica	–	13 m	15	7	34.6	N.R.	N.R.	Menu analysis
49	Cugini et al.[185]	ITA	Italian research station of Terra Nova Bay	–	> 1 m	10	40	35 ± 8	N.R.	N.R.	N.R.
50	Easty[186]	UK	Halley Bay, Antarctica	–	12 m	25	0	24.8 ± 1.9	74.2	N.R.	Weighed food records
51	Efimov et al.[187]	USSR	Ski expedition, Artctica	–	~ 2 m	N.R.	N.R.	N.R.	N.R.	N.R.	Standardized food rations
52	Efremov et al.[188]	USSR	Ski expeditions, Artctica	–	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	Weighed food records
53	Farrace et al.[137]	ITA	Dome C plateau, Antarctica	–	68 d	9	0	41.3 ± 5.4	N.R.	23.6 ± 1.3	Standardized expedition diet
54	Fernández-Riestra[189]	ESP	Research vessel Hespérides	–	96 d	17	0	32	N.R.	N.R.	Weighed food records
55	Garshenin[190]	USSR	Molodezhnaya Station, Bellingshausen Station, Antarctica	9th, 10th, and 13th Soviet expedition	~ 1 y	15–23	N.R.	N.R.	N.R.	N.R.	Standardized expedition diet
			Molodezhnaya Station, Antarctica	17th Soviet expedition	~ 1 m	N.R.	N.R.	N.R.	N.R.	N.R.	
56	Guenter et al.[191]	USA	Amundson-Scott South Pole Station, Antarctica	–	12 m	13	0	31.7 ± 9.9	85.1 ± 15.7	25.8 ± 3.9	N.R.
57	Gormly[192]	AUS	Mawson Station, Antarctica	Supplement group	9 m	14	0	29.2 ± 6.5	77.7 ± 9.6	N.R.	Frequency-based self-report with ascorbic-acid measurement using dipsticks
				Non-supplement group		14	0	27.9 ± 5.3	73.8 ± 8.5	N.R.	
58	Hicks[193]	AUS	Wilkes Station, Antarctica	–	12 m	18	0	29.2	74.6	23.7	N.R.
59	Iuliano and Ayton[126]	AUS	Davis Station, Mawson Station, Casey Station, Macquarie Island Antarctica	Males	12 m	188	0	42.8 ± 10.8	87.3 ± 13.7	27.5 ± 3.6	Mid-expedition 3-day weighed food records
				Females		37	100	35.1 ± 8.1	69.8 ± 12.1	25.1 ± 3.6	
60	Iuliano-Burns et al.[194]	AUS	Australian Antarctic or sub-Antarctic coastal stations, Antarctica	25(OH)D > 50 nmol/L	~ 12 m	68	16	41.7	83.2 ± 11.4	N.R.	Mid-expedition 3-day weighed food records
				25(OH)D < 50 nmol/L		52	15	38.0	85.9 ± 14.4	N.R.	
61	Iuliano-Burns et al.[195]	AUS	Davis Station, Mawson Station, Casey Station, Antarctica	12× Supplement	~ 12 m	37	16	41.5 ± 11.2	82.8 ± 12.1	N.R.	Mid-expedition 3-day weighed food records
				6× Supplement		38	19	39.7 ± 10.7	84.6 ± 3.2	N.R.	
				1× Supplement		35	10	42.6 ± 11.8	87.6 ± 11.6	N.R.	
62	Johnsen et al.[134]	NOR, USA	Ski expedition, Antarctica	–	93 d	1	0	34	84	N.R.	Planned rations with diary-based recorded intake
63	Junghans et al.[196]	GER	German Democratic Republic (GDR) Base Laboratory, Antarctica	–	13–17 m	6	0	37.0 ± 5.3	76.8 ± 18.1	24.7 ± 4.7	N.R.
64	Klos et al.[26]		Concordia Station, Antarctica	–	1 y	34	21	39.2 ± 10.9	76.8 ± 12.7	25.4 ± 3.4	FFQ

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Group 1: Space missions											
		GER, DEN, USA									
65	Masterton et al.[74]	UK	Britannia Sø Base, Greenland	–	~ 2 y	4	0	24.8 ± 1.3	79.3 ± 7.4	25.6 ± 0.9	Weighed food records
66	Masterton et al.[75]	UK	Greenland	–	~ 2 y	4	0	24.8 ± 1.3	79.3 ± 7.4	25.6 ± 0.9	Weighed food records
67	Matheson et al.[127]	AUS	Casey Station, Antarctica	Dietary Intervention Group, Standard diet	10 m	23	4	34.2 ± 8.0	76.4 ± 11.5	24.4 ± 3.2	4-Day weighed records, photo-verified portions
				Dietary Intervention Group, Intervention diet							
			Casey Station, Antarctica	Non-Intervention Group	12 m	18	11	24–47	75.3 ± 10.1	24.6 ± 3.2	1-Week group food record
68	Milan and Rodahl[197]	USA	Little America V, Antarctica	Scientist group	12 m	9	0	33	82	25.0	Weighed food records
				Navy group		4	0	28	81	26.2	
69	Netterstrøm et al.[198]	DEN	Fishing, Faroe Islands	–	2–3 m	96	0	41.7 ± 12.0	88.4 ± 14.6	27.7 ± 4.9	N.R.
70	Nieman et al.[199]	USA, GER	Ski expedition, Antarctica	–	8 w	1	0	33	81.4	N.R.	Daily dietary logs
71	O'Brien et al.[200]	UK, CHE, GER	Crossing of Antarctica	–	40 w	5	0	28–54	77.9 ± 9.6	26.4 ± 3.9	Dietary logs
72	Okubo[153]	JPN	Syowa Station, Antarctica and Traverse, Antarctica	Syowa Station, Traverse	1 y	11	0	27–50	68.6	N.R.	Daily dietary logs with nutrient analysis from Japanese food tables
			Syowa Station, Antarctica	Syowa Station		18	0	25–43	62.1	N.R.	
73	Oliveri et al.[201]	ARG	Belgrano II base, Antarctica San Martin base, Antarctica	–	12–14 m	17	0	30 ± 5	72.7 ± 9.1	24.6 ± 2.3	N.R.
74	Orr[202]	UK	Hope Bay, Antarctica	Hope Bay,	2 y	30	0	26	73.3	N.R.	N.R.
			Experimental Sledging journey	Sledging journey	15–70 d	10	0	N.R.	77.8	N.R.	
75	Palinkas et al.[76]	USA	McMurdo Station, Antarctica	McMurdo Station	4–11 m	104	45	35.8	N.R.	26.7 ± 4.4	N.R.
			Amundson-Scott South Pole Station, Antarctica	Amundson-Scott South Pole Station		81	21	39.3	N.R.	24.8 ± 4.6	
76	Palinkas et al.[77]	USA	McMurdo Station, Antarctica; Amundson-Scott South Pole Station, Antarctica	Summer group	91 ± 3 d	32	28	36.6 ± 1.6	N.R.	N.R.	N.R.
				Winter group	138 ± 3 d	41	46	36.9 ± 1.3	N.R.	N.R.	
77	Parent et al.[203]	CAN, UK	Ski expedition, Antarctica	–	32 d	6	50	25 ± 4	74.5 ± 13.6	23.5 ± 2.8	Prepackaged, weighed food rations
78	Parker[204]	UK	Halley Station, Antarctica	–	1 y	19	0	25.8 ± 0.8	78.1 ± 0.7	N.R.	N.R.
79	Pitson et al.[205]	AUS	Davis Station, Antarctica	–	~ 12 m	19	0	33.4	81.0	N.R.	N.R.
80	Popkin et al.[206]	USA	South Pole station, Antarctica	–	~ 6 m	22	0	N.R.	N.R.	N.R.	Diet history protocols
81	Premkumar et al.[14]	IND	Maitiri Station, Antarctica	–	13 m	20	0	39.0 ± 10.2	N.R.	N.R.	Diet history questionnaire, FFQ (Vitamin-D–focused).

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Group 1: Space missions											
82	Reed et al.[138]	USA	McMurdo Sound, Antarctica	–	44 w	15	0	24.5 ± 0.9	81.3 ± 2.7	N.R.	N.R.
83	Reed et al.[207]	USA	McMurdo Sound, Antarctica	–	~11 m	12	8	31.6 ± 1.8	N.R.	27.1 ± 1.1	N.R.
84	Sawhney et al.[208]	IND	Dakshin Gangotri Station, Antarctica	–	12 m	9	0	34.7 ± 0.3	68.6 ± 8.0	24.2 ± 2.5	N.R.
85	Simpson and Maynard[209]	UK	Rothera Research Station, Antartica	–	12 m	21	14	30.6 ± 6.0	84.0 ± 17.7	25.2 ± 3.3	3-Day diet records
86	Sletten et al.[210]	AUS	Davis Station, Mawson Station, Casey Station, Antarctica	–	6 m	51	20	45.5 ± 11.9	N.R.	26.3 ± 5.6	N.R.
87	Smith et al.[33]	USA	McMurdo Station	400 IU/d Supplement	5 m	18	28	42 ± 12	91.0 ± 22.0	29 ± 6	7-Day diet records (Vitamin-D–focused)
				1000 IU/d Supplement		19	32	44 ± 8	95.0 ± 22.0	31 ± 7	
				2000 IU/d Supplement		18	17	43 ± 10	89.0 ± 18.0	28 ± 6	
				Non- Supplement		7	57	39 ± 12	78.0 ± 22.0	28 ± 7	
88	Sonnenfeld et al.[211]	USA	Cave, New Mexico	–	131 d	1	100	27	50	N.R.	N.R.
89	Steinach et al.[212]	GER	Neumayer Station II and III, Antarctica	–	13–14 m	43	35	36.5 ± 9.1	77.5 ± 13.1	24.8 ± 3.3	N.R.
90	Strewe et al.[162]	GER	Neumayer Station, Antarctica	Neumayer Station	12 m	16	0	37.7 ± 2.3	N.R.	26.9 ± 0.8	N.R.
			Concordia Station, Antarctica	Concordia Station	12 m	15	0	39.1 ± 2.8	N.R.	24.7 ± 0.8	
91	Stroud[135]	UK	Sledging journey, Antarctica	–	70 d	3	0	32.0 ± 2.6	78.3 ± 7.4	24.1 ± 1.5	Pre-packed weighed rations
92	Stroud et al.[136]	UK	Walking expedition, Antarctica	–	96 d	1	0	37	74.8	N.R.	Weighed rations
				–		1	0	48	95.6	N.R.	
93	Taylor et al.[78]	AUS	Davis Station, Antarctica	Davis Station	48 w	30	7	24–46	74.9 ± 11.0	24.4	7-Day weighed food record
			Casey Station, Antarctica	Casey Station	48 w	18	11	24–47	75.3 ± 15.3	24.6	7-Day weighed food record
			Macquarie Island Station, Antarctica	Macquarie Island Station	48 w	14	21	24–54	78.7 ± 13.8	26.4	7-Day weighed food record
94	Taylor et al.[79]	AUS	Davis Station, Antarctica	–	48 w	30	7	24–46	74.9 ± 11.0	24.4	7-Day weighed food record
95	Taylor et al.[213]	UK, USA	Ski expedition, Antarctica	–	61 d	6	100	N.R.	72.8	23.1 ± 1.7	Weighed food records
96	Vats et al.[80]	IND	Ship voyage, followed by Maitri Station, Antarctica	–	~ 6 w	22	0	39.5 ± 8.5	60.8 ± 1.6	22.1 ± 1.6	Duplicate-plate sampling with laboratory nutrient analysis
97	Vats et al.[81]	IND	Ship voyage, followed by Maitri Station, Antarctica	–	~ 6 w	22	0	39.5 ± 8.5	N.R.	N.R.	Duplicate-plate sampling at random meals
98	Ventsenostsev[214]	USSR	Molodyozhnaya Station, Antarctica	–	~ 1 y	43	N.R.	21–53	N.R.	N.R.	N.R.
99	Wilson et al.[215]	UK	Ski expedition, Antarctica	–	47 d	9	33	28–63	79.7 ± 10.6	N.R.	Daily ration spreadsheets with logged consumption (%) and post-expedition verification
100	Woods et al.[216]	UK	Polar Expedition, Antarctica	–	42 d	20	0	36 ± 7	82.9 ± 7.8	25.8 ± 1.7	Standardized rations
101	Yonei et al.[217]	JPN	Syowa Station, Antarctica	–	~ 1 y	31	0	34.5 ± 7.3	66.0 ± 6.3	N.R.	Weighed food records
102	Zerath et al.[218]	FRA	Dumont d'Urville Station, Antarctica	–	~ 1 y	15	0	30.1 ± 10.3	74.0 ± 8.7	23.9 ± 2.4	N.R.

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Group 1: Space missions											
103	Zhang et al.[219]	CHN	Ship cruise	Placebo	30 d	42	0	25.8 ± 4.5	N.R.	22.9 ± 3.2	Weekly shipboard food supply record
				Probiotic		40	0	26.0 ± 3.9	N.R.	23.0 ± 1.9	
Group 2b: terrestrial ICC environments											
104	Agureev et al.[87]	RUS	Mars-500	–	105 d	6	N.R.	24–46	82.3 ± 11.5	25.6 ± 3.2	Standardized pre-portioned diet
105	Aufauvre-Poupon et al.[220]	FRA	Submarine	–	60 d	24	0	29.9 ± 6.5	76.0 ± 9.6	N.R.	N.R.
106	Barchukov et al.[221]	RUS	Submarine	–	75 d	48	0	19–25	N.R.	N.R.	Standardized fixed diet
107	Chabal et al.[222]	USA	Submarine	–	30 d	58	0	27.8 ± 5.9	N.R.	N.R.	N.R.
108	Custaud et al.[97]	FRA	SFINCCS-99	240 d-mission	240 d	4	0	41.5 ± 4.7	82.3 ± 10.6	26.1 ± 3.3	N.R.
				110 d-mission	110 d	4	0	38.0 ± 7.9	76.3 ± 6.1	24.6 ± 1.6	
109	Douglas et al.[223]	USA	HERA	Standard diet	45 d	16	38	40.0 ± 9.0	N.R.	23.7 ± 2.8	Controlled environment
				Enhanced diet							
110	Gasier et al.[128]	USA	Submarine	Body fat < 25%	3 m	20	0	20–39	75 ± 8	24 ± 2	Fred Hutchinson FFQ
				Body fat > 25%		33	0		96 ± 12	30 ± 3	Fred Hutchinson FFQ
111	Gilman et al.[224]	USA	Submarine	–	68 d	28	0	25.2	N.R.	N.R.	Intake questionnaire
112	Gilman et al.[225]	USA	Submarine	–	68 d	30	0	25.2	N.R.	N.R.	Intake questionnaire (Vitamin-D–focused)
113	Gunga et al.[226]	GER	Isolation facility	–	28 d	6	0	28.0 ± 2.7	78.2 ± 6.5	23.7 ± 2.7	Daily consumption log (fluids quantified; solids unhydrated)
114	Katchman et al.[227]	USA	Controlled activity facility	–	6 w	8	0	22.0 ± 1.8	70.8 ± 9.3	23.3 ± 2.8	Standardized diet, weighed food records
115	Kraft et al.[96]	USA, JPN, CAN	Closed environment simulating ISS flight conditions	240 d-mission	240 d	4	0	42.0 ± 4.6	81.3 ± 12.3	N.R.	Controlled environment
				110 d-mission	110 d	4	25	30.8 ± 4.8	65.8 ± 14.8	N.R.	
116	Lamb et al.[228]	USA	Space Cabin Simulator	–	30 d	10	0	21.0 ± 4.0	74.8 ± 11.0	N.R.	Controlled environment
117	Maillet et al.[92]	GER	Isolation facility	–	60 d	4	25	29.3 ± 1.7	76.5 ± 9.8	24.0 ± 2.4	Daily intake records
118	Maillet et al.[93]	GER	Isolation facility	–	60 d	4	25	29.3 ± 1.7	76.5 ± 9.8	24.0 ± 2.4	Daily intake records
119	Milon et al.[94]	CHE	Isolation facility	–	60 d	4	25	26.8 ± 2.2	76.5 ± 9.8	24.0 ± 2.4	Barcode-based monitored intake with weighed foods and automatic nutrient calculation
120	Muid et al.[90]	MYS	Mars-500	–	520 d	6	0	31.8 ± 4.8	N.R.	26.4 ± 2.5	Controlled environment
121	Nichiporuk et al.[88]	RUS	Mars-500	–	105 d	6	0	33.0 ± 2.3	84.8 ± 3.5	27.1 ± 1.9	Controlled environment
122	Paglia and Walford[15]	USA	BIOS-2	–	2 y	8	50	37.9 ± 13.1	N.R.	22.5	Daily intake records
123	Reynolds et al.[229]	USA	Submarine	–	3 m	23	0	18–35	N.R.	N.R.	Intake not assessed
124	Richalet et al.[230]	FRA	Hypobaric chamber	–	31 d	8	0	26.6 ± 4.3	74.3 ± 6.6	22.9 ± 1.5	

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Group 1: Space missions											
											Daily weighed intake recording; duplicate samples chemically analyzed
125	Rietjens et al.[231]	NLD	Submarine	–	12 w	13	0	27.8 ± 5.8	N.R.	24.8 ± 3.7	N.R.
126	Rose et al.[232]	USA	Decompression chamber	–	40 d	6	0	27.5 ± 2.2	83.0 ± 9.8	N.R.	Weighed food records
127	Sack et al.[233]	USA	Submarine	–	69 d	10	0	N.R.	N.R.	N.R.	Daily intake log
128	Schlichting et al.[234]	USA	Submarine	Nutrition group	2 m	11	0	18–35	N.R.	N.R.	Intake not assessed, daily supplement administration Record
				Control group		11					
129	Silverstone and Nelson[84]	USA	BIOS-2	–	2 y	8	50	37.9 ± 13.1	67.5 ± 13.2	N.R.	Weighed food records
130	Silverstone[86]	USA	BIOS-2	–	2 y	8	50	N.R.	67.5 ± 13.2	N.R.	Weighed food records
131	Sirmons et al.[235]	USA	HERA	–	30 d	16	44	29–52	N.R.	24.3	ISS FIT app intake logging (barcode/photo/voice) with weighed leftovers
132	Smith et al.[95]	USA	Ground-based chamber simulation	60 d-mission	60 d	4	N.R.	N.R.	N.R.	N.R.	Specialized 24-h FFQ, 7-d FFQ, 5-day weighed records
				91 d-mission	91 d	4	N.R.	N.R.	N.R.	N.R.	Specialized 24-h FFQ, 7-d FFQ, 5-day weighed records
133	Smith et al.[1,44]	USA	Ground-based chamber simulation	60 d-mission	60 d	4	25	26–41	56.8–83.4	22.8	Specialized 24-h FFQ, 7-d FFQ, 5-day weighed records
				91 d-mission	91 d	4	50	26–41	56.8–83.4	22.8	Specialized 24-h FFQ, 7-d FFQ, 5-day weighed records
134	Strollo et al.[89]	ITA	Mars-500	–	105 d	6	0	32.7 ± 5.9	83.2 ± 12.6	25 ± 3	Individualized, controlled daily menus
135	Strollo et al.[91]	ITA	Mars-500	–	520 d	6	0	32.0 ± 4.7	81.5	26.0	N.R.
136	Thornton and Ord[2,43]	USA	Ground-based chamber simulation	–	56 d	3	0	N.R.	N.R.	N.R.	Weighed food records
137	Titze et al.[236]	FRA, GER, RUS	HUBES	–	135 d	3	0	35.0 ± 2.7	72.5 ± 7.7	23.2 ± 1.7	Barcode–based daily intake recording
138	Walford et al.[85]	USA	BIOS-2	–	2 y	8	50	37.9 ± 13.1	N.R.	23.0 ± 3.4	Weighed food records
Group 2c: terrestrial ICC studies reflecting microgravity-like physiological adaptations											
139	Austermann et al.[98]	GER, FRA	6° HDBR	–	60 d	20	0	34.0 ± 8.0	74.0 ± 6.0	24.0 ± 2.0	Controlled environment
140	Austermann et al.[99]	GER, USA	6° HDBR	Nutrition group	60 d	10	0	35.0 ± 7.0	73.0 ± 6.0	24.0 ± 2.0	
				Controll group		10	0	34.0 ± 9.0	75.0 ± 9.0	24.0 ± 2.0	
141	Barbacini et al.[100]	ITA, GER	6° HDBR	Nutrition group	60 d	10	0	34.0 ± 7.8	73.5 ± 6.1	23.7 ± 1.5	Controlled environment
				Controll group		10					
142	Belavý et al.[237]	GER	6° HDBR	Controll group	60 d	9	0	33.1 ± 7.8	80.6 ± 5.2	N.R.	Controlled environment
				Excercise group		8	0	31.1 ± 5.1	75.0 ± 12.8	N.R.	
				Excercise + Vibration group		7	0	32.2 ± 10.4	81.5 ± 6.2	N.R.	

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Table 2 (continued) | Overview of single study characteristics

Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
143	Beller et al.[105]	GER	6° HDBR	Controll group	60 d	8	100	34.4 ± 3.8	56.5 ± 3.3	21.4 ± 1.5	Controlled environment
				Excercise group		8	100	32.8 ± 3.4	59.5 ± 5.7	21.9 ± 1.4	
				Nutrition group		8	100	29.4 ± 3.5	61.6 ± 4.8	21.3 ± 1.2	
144	Bergouignan et al.[28]	FRA	6° HDBR	Controll group	60 d	8	100	34.0 ± 4.0	55.6 ± 3.8	21.3 ± 1.4	Controlled environment
				Excercise group		8	100	33.0 ± 4.0	58.4 ± 6.5	21.7 ± 1.4	
145	Bilancio et al.[238]	ITA	6° HDBR	–	35 d	10	0	23.8 ± 0.5	73.7 ± 9.8	N.R.	Controlled environment
146	Blanc et al.[239]	FRA	6° HDBR	–	42 d	8	0	28.1 ± 2.5	74.9 ± 8.7	24.1 ± 2.1	Controlled environment
147	Bleeker et al.[240]	NLD	6° HDBR	Controll group	52 d	8	0	34 ± 3	79.5 ± 3.8	23.5	Controlled environment
				Excercise group		8	0	33 ± 2	76.8 ± 1.8	23.2	
148	Bychkov and Markaryan[115]	USSR	4° HDBR	Controll group	91 d	3	0	26–40	N.R.	N.R.	Controlled environment
				Nutrition group		5	0	26–40	N.R.	N.R.	
149	Bychkov et al.[116]	USSR	4° HDBR	Controll group	49 d	3	0	36–40	71.8 ± 9.8	N.R.	N.R.
				Nutrition group		5	0	36–40		N.R.	
150	Bychkov et al.[117]	USSR	4° HDBR	Controll group	49 d	8	N.R.	N.R.	N.R.	N.R.	Controlled environment
			4.5° HDBR	Nutrition group	182 d	6	N.R.	N.R.	N.R.	N.R.	
				Nutrition and exercise group		6	N.R.	N.R.	N.R.	N.R.	
151	Clement et al.[241]	USA	6° HDBR	–	30 d	11	45	25–50	N.R.	N.R.	Controlled environment
152	Chopard et al.[106]	CAN, FRA	6° HDBR	Controll group	60 d	8	100	34.0 ± 3.0	56.2 ± 3.6	N.R.	Controlled environment
				Excercise group		8	100	32.0 ± 3.0	59.1 ± 6.1	N.R.	
				Nutrition group		8	100	29.0 ± 3.0	61.7 ± 4.8.-1	N.R.	
153	Cromwell et al.[122]	USA	6° HDBR	Controll group	70 d	37	3	33.2 ± 7.0	77.3 ± 10.5	N.R.	Controlled environment
				Excercise group							
154	Dorfmann et al.[107]	USA	6° HDBR	Controll group	60 d	8	100	32.1 ± 4	59 ± 4 kg	N.R.	Controlled environment
				Excercise group	60 d	8	100	32.1 ± 4	59 ± 4 kg	N.R.	
				Nutrition group	60 d	8	100	32.1 ± 4	59 ± 4 kg	N.R.	
155	Downs et al.[123]	USA	6° HDBR	Controll group	70 d	9	0	38.1 ± 7.8	81.4 ± 7.7	N.R.	Controlled environment
				Excercise group		8	0	42.3 ± 5.7	77.0 ± 13.9	N.R.	
				Excercise and testosterone group		9	0	42.0 ± 6.5	75.4 ± 6.4	N.R.	
156	Elmann-Larsen and Schmitt[242]	NLD	6° HDBR	Control group	90 d	7	0	N.R.	N.R.	N.R.	Controlled environment
				Excercise group		9					
				Medication group		9					
157	Fernandez-Gonzalo et al.[243]	SWE	6° HDBR	Control group	84 d	9	0	33 ± 5	71 ± 6	N.R.	Controlled environment incl.-controlled diet
				Excercise group		12	0	32 ± 4	72 ± 5	N.R.	

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Table 2 (continued) | Overview of single study characteristics

Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
158	Gharib et al.[244]	FRA	6° HDBR	LBNP group	30 d	5	0	32.0 ± 1.9	75.0 ± 4.6	N.R.	N.R.
				Control group		5	0	32.2 ± 1.7	74.8 ± 3.8	N.R.	
159	Greenleaf et al.[118]	USA	6° HDBR	Control group	30 d	5	0	36.0 ± 1.0	76.5 ± 1.8	N.R.	Controlled environment
				Isotonic training		7	0				
				Isokinetic training		7	0				
160	Greenleaf[119]	USA	6° HDBR	Control group	30 d	5	0	36.0 ± 4.0	74.6 ± 11.9	N.R.	N.R.
				Isotonic training		7	0	36.0 ± 4.0	80.2 ± 4.1	N.R.	
				Isokinetic training		7	0	36.0 ± 4.0	74.3 ± 6.2	N.R.	
161	Heer et al.[108]	GER, USA	6° HDBR	Control group	60 d	8	100	32.4 ± 3.7	59.0 ± 5.0	N.R.	Controlled environment
				High Protein group		8	100			N.R.	
162	Inniss et al.[124]	USA	HDBR	–	60–90 d	13	38	35.5 ± 9.6	72.6 ± 16.2	N.R.	Controlled environment
163	Iovino et al.[245]	ITA	6° HDBR	–	35 d	10	0	23.2 ± 2.2	74.7 ± 9.5	23.3 ± 1.9	Controlled environment.
164	Kermorgant et al.[101]	FRA, NLD	HDBR	Controll group	60 d	10	0	34.0 ± 8.0	74.0 ± 7.0	N.R.	Controlled environment.
				Treatment group		10	0			N.R.	
165	Lee et al.[125]	USA	6° HDBR	Control group	30 d	7	100	24.0 ± 3.0	57.8 ± 4.3	N.R.	Controlled environment
				Excercise group		7	100		55.3 ± 3.2	N.R.	
166	Lee et al.[109]	USA	6° HDBR	Excercise group	60 d	8	100	33.0 ± 2.8	58.1 ± 6.2	N.R.	Controlled environment
				Control group		8	100	34.0 ± 2.8	55.8 ± 4.0	N.R.	
				Nutrition group		8	100	31.0 ± 2.8	61.1 ± 4.5	N.R.	
167	Lemoine et al.[110]	USA	6° HDBR	Controll group	60 d	8	100	34.0 ± 2.8	55.6 ± 4.0	N.R.	Controlled environment
				Excercise group		8	100	33.0 ± 2.8	58.1 ± 6.2	N.R.	
				Nutrition group		8	100	29.0 ± 2.8	61.2 ± 4.5	N.R.	
168	Liu et al.[246]	CHN, BEL	6° HDBR	–	60 d	14	0	30.0 ± 1.0	62.0 ± 1.0	N.R.	Controlled environment
169	Morgan et al.[247]	USA	6° HDBR	–	30 d	12	33	32.0 ± 8.0	73.6 ± 10.6	24.5 ± 2.8	Controlled environment
170	Noone et al.[102]	IRE, USA, FRA	6° HDBR	Controll group	60 d	10	0	33.5 ± 8.5	73.7 ± 8.5	24.1 ± 0.7	Controlled environment
				Treatment group		10	0	34.8 ± 7.5	72.1 ± 5.7	23.8 ± 0.6	
171	Rai et al.[248]	BEL, USA, IND	6° HDBR	–	60 d	20	0	18–22	72.5 ± 3.2	N.R.	N.R.
172	Rejc et al.[249]	ITA, SVN, UK	6° HDBR	–	35 d	10	0	23.1 ± 2.2	74.7 ± 9.4	N.R.	Controlled environment
173	Ritz et al.[120]	FRA	6° HDBR	–	42 d	7	0	28.0 ± 2.4	74.3 ± 9.3	23.8 ± 2.1	Controlled environment
174	Ritz et al.[121]	FRA	6° HDBR	–	42 d	7	0	28.0 ± 2.4	74.3 ± 9.3	23.8 ± 2.1	Controlled environment
175	Sakowski et al.[250]	USA	6° HDBR	–	90 d	20	30	35.5 ± 7.7	N.R.	N.R.	Controlled environment

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Table 2 (continued) | Overview of single study characteristics

Study ID	Author, year	Origin	Type of intervention	Study group	Study duration	Sample size [*n*]	Sex [%f]	Age [years]	Weight [kg]	BMI [kg/m^2]	Dietary assessment method
Group 1: Space missions											
176	Scheld et al.[171]	GER	6° HDBR	–	16 w	6	0	30.3 ± 7.8	79.3 ± 18.6	N.R.	Controlled environment
177	Schneider et al.[111]	USA	6° HDBR	Controll group	60 d	8	100	34.0 ± 4.0	56.3 ± 3.0	N.R.	Controlled environment
				Excercise group		8	100	33.0 ± 4.0	58.4 ± 6.4	N.R.	
				Nutrition group		8	100	31.0 ± 4.0	61.3 ± 4.5	N.R.	
178	Spaak et al.[172]	SWE	6° HDBR	–	120 d	6	N.R.	31	80	N.R.	Controlled environment
179	Stratis et al.[103]	CAN	6° HDBR	Controll group	60 d	10	0	34.0 ± 8.0	73.5 ± 1.5	N.R.	N.R.
				Nutrition group		10	0			N.R.	
180	Taibbi et al.[251]	USA	6° HDBR	Controll group	70 d	6	17	39.3 ± 7.6	76.2 ± 9.2	25.9 ± 2.0	Controlled environment
				Excercise group		9	0	34.1 ± 5.1	77.0 ± 9.1	23.3 ± 2.7	
181	Trappe et al.[112]	USA	6° HDBR	Control group	60 d	8	100	34.0 ± 1.0	55.6 ± 1.4	N.R.	Controlled environment
				Nutrition group		8	100	29.0 ± 1.0	61.2 ± 1.6	N.R.	
				Exercise group		8	100	33.0 ± 1.0	58.1 ± 2.2	N.R.	
182	Trappe et al.[113]	USA	6° HDBR	Control group	60 d	8	100	34.0 ± 1.0	55.6 ± 1.4	N.R.	Controlled environment
				Nutrition group		8	100	29.0 ± 1.0	61.2 ± 1.6	N.R.	
				Exercise group		8	100	33.0 ± 1.0	58.1 ± 2.2	N.R.	
183	Trappe et al.[114]	USA	6° HDBR	Control group	60 d	7	100	34.0 ± 1.0	57.0 ± 1.0	21.0 ± 1.0	Controlled environment
				Nutrition group		8	100	29.0 ± 1.0	62.0 ± 2.0	21.0 ± 1.0	
				Exercise group		6	100	33.0 ± 1.0	58.0 ± 3.0	22.0 ± 1.0	
184	Trim et al.[104]	UK	6° HDBR	-	60 d	20	0	34 ± 8	72.9 ± 7.1	23.5 ± 1.8	Controlled environment
185	Vinci et al.[139]	ITA	6° HDBR	Conventional diet group	60 d	8	0	32 ± 4	55.6 ± 3.9	N.R.	Controlled environment
				High Protein diet group		8			61.0 ± 4.4	N.R.	
186	Zachwieja et al.[252]	USA	6° HDBR	Treatment group	28 d	6	0	36.3 ± 6.3	78.9 ± 12.0	N.R.	Controlled environment
			6° HDBR	Placebo group	28 d	4	0	35.2 ± 7.4	82.0 ± 14.2	N.R.	

Age, Weight, and Body-Mass-Index (BMI) are indicated as mean ± standard deviation (SD). Superscript numbers indicate studies that are listed across multiple habitat categories.

ARG Argentina, *AUS* Australia, *BEL* Belgium, *CAN* Canada, *CHE* Switzerland, *CHN* China, *EO* Expedition operation, *FRA* France, *d* day, *DEN* Denmark, *ESP* Spain, *GER* Germany, *GRC* Greece, *HC* hermetical chamber, *HDBR* head-down bed rest, *ICE* isolated, confined and extreme, *ICC* isolated, confined and controlled, *IND* India, *IRE* Ireland, *ISR* Israel, *ISS* International Space Station, *ITA* Italia, *m* month, *JPN* Japan, *KOR* Korea, *MYS* Malaysia, *N.R.* not reported, *NLD* The Netherlands, *NOR* Norway, *RUS* Russia, *SFINCCS* Simulation of a Flight of International Crew on Space Station, *SLE* Slovenia, *SWE* Sweden, *UK* United Kingdom, *USA* United States of America, *USSR* Union of Soviet Socialist Republics, *w* week, *y* year, *ZAF* Republic of South Africa.

cold exposure and physical exertion; while standardized in composition, these rations were often consumed flexibly according to individual needs.

ICC environments encompassed intermediate levels of dietary control. Operational settings, such as submarines, commonly employed partially standardized menus, with access to fresh produce decreasing over the course of deployment. In contrast, controlled isolation studies (e.g., Mars-500, metabolic chamber experiments) generally implemented tightly regulated experimental diets with predefined nutrient profiles.

Across all habitat types, preserved foods constituted the foundation of dietary provision. However, systematic differences were evident with respect to dietary autonomy, the presence of explicit dietary targets, fresh-food availability, and the use of energy-dense rations: dietary control and defined metabolic targets were most pronounced in spaceflight and bed-rest studies, intermediate in ICC environments, and least constrained yet most strongly shaped by environmental and logistical factors in terrestrial ICE settings.

Energy and macronutrient intake variability scale with environmental demands, with bed rest representing the most controlled condition

Spaceflight. Across spaceflight missions, macronutrient provision was relatively consistent; however, reported energy intake was generally lower than prescribed energy provision (commonly > 3000 kcal/day) and showed substantial variability across studies. Based on available intake data, mean reported energy intake was 2452 ± 410 kcal/day, with values ranging from 1720 to 3002 kcal/day (Fig. 2). Planned macronutrient provision across missions averaged approximately 50 E% carbohydrates (range 45–53 E%), 32 E% fat (range 30–36 E%), and 17 E% protein (range 16–19 E%). In contrast, quantitatively assessed macronutrient intake was reported in only a single study (which was used by multiple studies), which documented an intake distribution of 57 E% carbohydrates, 27 E% fat, and 16 E% protein (Fig. 3a)[51]. This limited reporting highlights both the scarcity of intake-level macronutrient data and the potential for divergence between prescribed dietary targets and actual consumption. Micronutrient adequacy was typically addressed through menu design and routine multivitamin supplementation. In addition, several missions reported the use of end-of-flight water–salt supplementation to acutely expand plasma volume and stabilize fluid and electrolyte balance prior to re-entry, with the aim of reducing the risk of orthostatic intolerance[53,56,58,60–62,64] (Table 3).

Terrestrial ICE environments. In terrestrial ICE environments, reported nutrient intake reflected substantial logistical constraints and highly variable workload demands, resulting in wide ranges of energy intake and heterogeneous micronutrient profiles. Across studies, reported energy intake ranged from 1320 to 7050 kcal/day, spanning low-activity winter-over periods and high-demand field expeditions (Fig. 2), with a mean intake of 3485 ± 1266 kcal/day.

Mean macronutrient intake across terrestrial ICE settings approximated 46 E% carbohydrates, 38 E% fat, and 15 E% protein, with considerable variability (25–60 E% carbohydrates, 23–68 E% fat, and 7–30 E% protein; Fig. 3b). Higher relative contributions of fat and protein were more frequently reported in studies conducted under high workload conditions, with protein intakes occasionally reaching 1.2–1.7 g/kg/day, consistent with the increased energy density and protein content of rations used during sustained physical exertion and cold exposure. Information on within-individual dietary changes over time or on mission-specific factors such as alcohol availability was rarely reported and therefore could not be systematically evaluated

Dietary fiber intake was infrequently reported[26,78,126,127]. When available, reported values generally ranged between 20 and 30 g/day. One study reported substantially lower fiber intake (~10 g/day); however, this was attributed by the authors to considerable underreporting associated with the food frequency questionnaire used[26].

Micronutrient intake exhibited pronounced variability across terrestrial ICE environments, largely reflecting dependence on food supply cycles and the availability of fresh produce. Some station-based diets reported intakes consistent with recommended levels for calcium, phosphorus, iron, and selected B vitamins (e.g., calcium 690–1520 mg/day; phosphorus 1090–1780 mg/day; iron 11–17 mg/day; riboflavin 1.3–2.4 mg/day). In contrast, other settings reported lower intakes of vitamin C, vitamin A, or calcium during periods of limited fresh-food availability (e.g., vitamin C 50–65 mg/day; vitamin A 0.8–1.6 mg/day; calcium 440–600 mg/day).

In several settings, vitamin C intake was increased through food fortification or supplementation (e.g., ~300 mg/day added or 1000 mg/day supplemental ascorbate). Vitamin D intake also varied markedly across studies, typically ranging from 0 to 150 IU/day from dietary sources alone. Consequently, several winter-over studies reported routine vitamin D supplementation (100–2000 IU/day, depending on program) to maintain circulating 25-hydroxyvitamin D concentrations under conditions of prolonged sunlight deprivation (Table 3).

Terrestrial ICC environments. Terrestrial ICC environments generally exhibited more controlled dietary intake patterns than terrestrial ICE settings. Across studies, reported energy intake averaged 2334 ± 409 kcal/day and typically ranged from 1260 to 3500 kcal/day (Fig. 2), although planned energy targets were not consistently achieved.

Macronutrient composition was comparatively stable across ICC protocols, with mean intakes of approximately 53 E% carbohydrates, 31 E% fat, and 16 E% protein, falling within observed ranges of 46–55 E% carbohydrates, 28–40 E% fat, and 14–20 E% protein (Fig. 3c). Dietary fiber intake was infrequently reported; where available, values in operational ICC settings such as submarines were generally moderate (approximately 20–23 g/day)[128].

A notable exception was the Biosphere 2 mission[15,84–86], in which unexpectedly low agricultural yields resulted in sustained energy deficits and substantial deviations from intended macronutrient profiles (approximately 75 E% carbohydrates, 12.5 E% fat, and 12.5 E% protein), accompanied by markedly higher fiber intake (~47 g/day) due to the predominantly plant-based closed-system diet[85].

Micronutrient intake varied considerably across ICC missions. Routine supplementation was common and included multivitamins, vitamin D (ranging from approximately 400 IU/day in daily regimens to intermittent doses up to 50,000 IU), and iron (approximately 10–15 mg/day). Across controlled ISS-type protocols, reported calcium intake typically ranged from 670 to 1200 mg/day, iron from 15 to 27 mg/day, and sodium from 2300 to 4800 mg/day. In the Mars-105 study, sodium intake was explicitly controlled to approximately 4700, 3500, 4700, and 2400 mg sodium/day (12–9–12–6 g NaCl/day).

Despite these controls, several studies reported micronutrient intakes below recommended levels, including vitamin A intake below 10% of the RDA, persistently low thiamine intake, and niacin intake approaching lower adequacy thresholds[84,86,94] (Table 3).

Terrestrial ICC studies reflecting microgravity-like physiological adaptations. Bed-rest studies were characterized by a high degree of dietary control and standardization relative to other habitat types, resulting in comparatively low variability in reported intake and enabling detailed assessment of diet-related physiological responses. Across studies, reported energy intake ranged from 1560 to 2940 kcal/day (Fig. 2), with a mean intake of 2330 ± 416 kcal/day. Although these levels were intended to match predefined metabolic targets (≈1.1–1.6 × resting metabolic rate based on Harris–Benedict estimations), actual intake was frequently below planned provision.

Macronutrient distribution exhibited limited variability across bed-rest protocols, with mean values of approximately 55 E% carbohydrates, 29 E% fat, and 16 E% protein, generally falling within reported ranges of 48–63 E% carbohydrates, 17–35 E% fat, and 13–21 E% protein (Fig. 3d). Protein prescriptions commonly began at approximately 1.0 g/kg/day and were increased to 1.2–1.6 g/kg/day in high-protein intervention arms designed to attenuate muscle loss during prolonged unloading.

Micronutrient intake was typically tightly regulated through fixed menus specifying sodium, potassium, calcium, and phosphorus content and was complemented by selective supplementation strategies, including vitamin D, multivitamins, and polyphenol- or omega-3–based formulations. In contrast, some protocols deliberately withheld supplementation to isolate nutrition-specific physiological effects (Table 3).

All environments. Across habitat types, a systematic gradient in the degree of dietary control can be observed, ranging from highly regulated bed-rest protocols to the most variable terrestrial ICE environments, with spaceflight and terrestrial ICC settings positioned between these extremes. This gradient is reflected in the macronutrient distributions illustrated in Fig. 3e, f.

Both the weighted mean analysis, which assigns greater influence to studies with larger sample sizes, and the unweighted mean analysis, which treats all studies equally and thereby emphasizes habitat-level characteristics, revealed consistent patterns. Specifically, ICC studies clustered closely around comparable macronutrient profiles, spaceflight studies displayed moderate dispersion, and terrestrial ICE studies showed the greatest variability, both in the distance of their overall mean from other habitat categories and in the dispersion observed across individual studies. As dietary intake in many studies was assessed using self-reported methods, some degree of reporting bias cannot be excluded.

The unweighted analysis (Fig. 3f) most clearly illustrates this gradient, as it highlights structural differences between habitat types independent of cohort size.

Body mass loss emerged as a common outcome, though the magnitude and variability differed markedly across habitats

Across habitats, a general tendency toward weight loss was reported most frequently (Table 3). To quantify weight-change dynamics, we extracted pre- and end-of-isolation (or nearest available) body mass values from the 104 studies reporting such outcomes (Fig. 4a–e), enabling calculation of Δ-values. Absolute changes in body mass are additionally reported in Supplementary Table S1 and Supplementary Fig. S1.

Spaceflight. In spaceflight studies, body-mass loss or tendencies toward loss were reported in 50% of cases, while 15% documented weight gain and 7.5% reported stable weight; 27.5% lacked weight-change information (Table 3). Among studies providing quantitative data ($n = 15$), mean body mass decreased by 3.0% (−2.0 kg), with individual trajectories ranging from −9.3% (−6.5 kg) to +2.2% (+1.6 kg) (Fig. 4a).

Terrestrial ICE environments. Reports of body-mass loss were less frequent in terrestrial ICE environments (37%), alongside 16% reporting weight gain and 23% reporting stable weight; 24% did not provide weight-change data (Table 3). Among studies with quantitative outcomes ($n = 41$), variability was particularly pronounced relative to other habitat types. Mean body mass decreased by 2.8% (−2.2 kg), with individual changes spanning −29.1% (−21.8 kg) to +5.7% (+4.6 kg) (Fig. 4b). Here, study duration appeared to be associated with proportional weight change, with longer studies tending toward smaller relative losses (Fig. 4b).

Terrestrial ICC environments. In terrestrial ICC settings, 42% of studies reported body-mass loss or tendencies toward loss, 18% reported weight gain, and 22% documented stable weight; 18% did not report weight-change outcomes (Table 3). Across studies with quantitative data ($n = 22$), mean body mass declined by 2.6% (−1.9 kg), with individual values ranging from −13.3% (−9.0 kg) to +7.6% (+6.25 kg) (Fig. 4c), with the most pronounced losses attributable to the sustained energy deficit documented in the Biosphere 2 mission (agriculturally produced, plant-based diet under conditions of unexpectedly low crop yields).

Terrestrial ICC studies reflecting microgravity-like physiological adaptations. In ICC environments inducing microgravity-like physiological changes, 48% of studies reported weight loss or tendencies toward loss, whereas 6% indicated weight gain and 17% stable outcomes; 29% did not provide weight-change data (Table 3). Among studies with quantitative values ($n = 26$), mean body mass decreased by 2.2% (−1.5 kg), with individual changes ranging from −6.0% (−3.4 kg) to +3.8% (+3.0 kg) (Fig. 4d).

Biochemical, electrolyte, and micronutrient markers, including vitamin D, showed heterogeneous changes across habitats, with adequate vitamin D status maintained only through supplementation

Across studies, vitamin D (Fig. 5) and electrolyte markers (Supplementary Figure S2) were the most frequently reported biochemical outcomes; further nutrition-specific data are provided in Supplementary Table S2.

Spaceflight. Across studies reporting serum calcium concentrations, 40% (4/10) showed increases, 10% (1/10) decreases, and 50% (5/10) no change. A comparable pattern was observed for urinary calcium, with 53% (9/17) of studies reporting increases, 18% (3/17) decreases, and 29% (5/17) no change, indicating substantial variability across studies. Sodium-related outcomes differed from these patterns, as decreases were reported in 71.4% (5/7) of studies, whereas increases and stable values were each reported in 14.3% (1/7). Phosphate responses were more uniform, with elevated concentrations reported in 80% (4/5) of studies. In contrast, potassium exhibited bidirectional changes, with increases reported in 43% (3/7) and decreases in 57% (4/7) of studies. Magnesium showed the greatest consistency across available reports, with decreases observed in all studies providing relevant data (3/3). Complementary analyses of trace-element[30,61,129] indicated reductions in iron, zinc, and selenium concentrations, in some cases accompanied by altered urinary excretion patterns.

Vitamin-related outcomes followed a broadly similar trend. Studies assessing vitamin status most frequently reported reduced or unchanged circulating 25-hydroxyvitamin D concentrations (5/6), alongside decreases in folate, retinol, and several tocopherol isoforms.

Metabolic markers also suggested context-dependent adaptations. Among studies reporting glucose concentrations, lower levels were observed in 60% (3/5) of reports. Lipid-related outcomes were more selective: total cholesterol declined in 75% (3/4) of studies, with no increases reported, whereas triacylglycerol concentrations displayed greater variability, with decreases reported in 50% (3/6), increases in 33% (2/6), and no change in 17% (1/6).

Markers related to protein and nitrogen metabolism further reflected heterogeneous responses. Increases in creatinine concentrations were reported in 62.5% (5/8) of studies, while decreases were less frequently observed (12.5%; 1/8). Total protein concentrations declined in 50% (5/10) of studies, and albumin showed a similar pattern, with reductions reported in 50% (2/4) of cases.

Terrestrial ICE environments. Reported mineral and electrolyte outcomes were heterogeneous and generally less pronounced than those observed in spaceflight settings. Serum calcium concentrations showed no consistent directional pattern, with increases and decreases each reported in 20% (3/15) of studies, while the majority (60%) reported no change. Sodium was assessed in a single study, which reported a decrease. Phosphate responses were mixed, with increases reported in 43% (3/7) of studies, decreases in 14% (1/7), and stable values in 43% (3/7). Potassium concentrations increased in the only study reporting this outcome, whereas magnesium concentrations remained unchanged across all available reports (5/5). Urinary calcium excretion also showed a mixed pattern, with one study reporting a decrease and one reporting no change (1/2 each).

Vitamin D status exhibited similarly broad variability. Among studies assessing circulating 25-hydroxyvitamin D concentrations, decreases were reported in 56% (9/16) of studies, while increases were observed in 31% (5/16) and stable values in 13% (2/16). This distribution suggests that reduced vitamin D availability is relatively common in terrestrial ICE environments, particularly during periods or settings characterized by minimal sunlight exposure.

Lipid-related outcomes were likewise heterogeneous. Total cholesterol increased in 42.9% (6/14) of studies, decreased in 35.7% (5/14), and remained unchanged in 21.4% (3/14). High-density lipoprotein (HDL) cholesterol was most frequently reported as stable (50%; 5/10), with fewer studies documenting increases (20%; 2/10) or decreases (30%; 3/10). Low-density lipoprotein (LDL) cholesterol tended to decline, with reductions reported in 62.5% (5/8) of studies. Triacylglycerol concentrations showed comparable variability but most commonly decreased (60%; 9/15), with the remaining studies split between increases (20%; 3/15) and no change (20%; 3/15).

Markers related to protein and nitrogen metabolism reflected similar variability. Creatinine concentrations decreased in 50% (2/4) of studies, increased in 25% (1/4), and remained unchanged in 25% (1/4). Total protein was reported in a single study and showed a decline, whereas albumin concentrations decreased in two-thirds of reporting studies (66.7%) and increased in the remaining third.

Terrestrial ICC environments. Across terrestrial ICC environments, reported mineral and electrolyte outcomes were heterogeneous and did not exhibit a consistent directional pattern. Serum calcium changes were evenly distributed across directions, with increases reported in 40% (2/5) of studies, decreases in 20% (1/5), and stable values in 20% (2/5). Sodium concentrations remained largely unchanged in the majority of reporting studies (80%; 4/5). Potassium concentrations declined in 80% (4/5) of studies and remained stable in the remainder. Magnesium, assessed in two studies only, either increased or remained stable.

Vitamin D status showed a more consistent pattern, with decreases in circulating concentrations reported in 86% (6/7) of studies.

In contrast, glucose-related outcomes were more variable. Reduced glucose concentrations were reported in 40% (2/5) of studies, while 40% (2/5) reported no change and 20% (1/5) observed increases, indicating modest and inconsistent alterations in glycemic regulation.

Lipid-related outcomes likewise displayed substantial heterogeneity. Total cholesterol decreased in 60% (6/10) of studies, while increases and stable values were each reported in 20% (2/10). HDL and LDL cholesterol followed similar patterns, with decreases reported in 67% (4/6), increases in 17% (1/6), and no change in 17% (1/6) of studies for each marker. Triacylglycerol concentrations showed no dominant direction, declining in 44% (4/9) and increasing in 44% (4/9) of studies, with stable values in the remaining 11% (1/9).

Protein-related markers were assessed less consistently. Available data indicated modest and variable responses: creatinine changes were evenly distributed across increases, decreases, and stable values (each 33.3%; 2/6). Total protein decreased in two studies and remained stable in one, while albumin was unchanged in two studies and decreased in one study employing a diet enriched in fruits, vegetables, and fish.

Terrestrial ICC studies reflecting microgravity-like physiological adaptations. Across ICC studies inducing microgravity-like physiological changes, reported physiological responses appeared more consistent than those observed in other terrestrial settings. Mineral-related outcomes showed the most coherent patterns. Serum calcium concentrations increased in 80% (4/5) of reporting studies, while urinary calcium excretion increased in all available reports (100%; 5/5). Phosphate concentrations likewise increased in 75% (3/4) of studies. In contrast, sodium and magnesium concentrations remained unchanged across all studies assessing these markers (4/4 and 1/1, respectively). Potassium concentrations were predominantly stable (75%; 3/4), with decreases reported in a minority of studies (25%; 1/4).

Vitamin D–related outcomes followed a similar directional tendency. Decreases in circulating 25-hydroxyvitamin D concentrations were reported in 60% (3/5) of studies, whereas increases and stable values were each reported in 20% (1/5).

Lipid-related markers were reported less frequently and did not demonstrate a consistent directional pattern. Total cholesterol increased in two-thirds of reporting studies (66.7%; 2/3), whereas HDL cholesterol decreased in the single study assessing this marker. LDL cholesterol and triacylglycerol concentrations remained unchanged in all available reports (1/1 each).

Protein-related outcomes showed modest but heterogeneous responses. Changes in creatinine concentrations were evenly distributed across increases, decreases, and stable values (each 33.3%; 2/6). In contrast, total protein and albumin concentrations decreased in two-thirds of reporting studies (66.7%; 2/3) and remained unchanged in the remainder (33.3%; 1/3). This pattern was observed even in studies implementing targeted nutritional or protein-focused interventions.

All environments. Across all habitat categories, vitamin D was the micronutrient most consistently reported to be affected. Decreases in circulating 25-hydroxyvitamin D concentrations were observed in studies that did not include vitamin D supplementation, irrespective of the specific environment. Conversely, increases in vitamin D status were reported exclusively in studies administering vitamin D supplements (Fig. 5). This pattern suggests that reduced ultraviolet exposure associated with confinement is the dominant determinant of declining vitamin D status, with inactivity and operational constraints potentially contributing indirectly, and that adequate supplementation is required to maintain circulating 25-hydroxyvitamin D concentrations.

Beyond vitamin D, physiological responses differed markedly across environments. Spaceflight showed the most consistent biochemical profile, characterized by coordinated alterations in mineral homeostasis, including calcium mobilization, reductions in magnesium and selected trace elements, and declines in circulating protein- and lipid-related markers. Head-down bed rest studies demonstrated partial overlap with spaceflight, particularly with respect to calcium mobilization and urinary calcium loss, as well as declines in vitamin D and circulating proteins; however, metabolic and lipid responses were less consistent, indicating that mechanical unloading reproduces some, but not all, microgravity-associated adaptations. Importantly, alterations in serum and particularly urinary calcium in spaceflight and head-down bed rest primarily reflect unloading-related bone resorption rather than dietary calcium intake. In contrast, terrestrial ICE and ICC environments exhibited pronounced heterogeneity, with no metabolic or nutritional pathway displaying uniform directional changes, suggesting a strong influence of contextual factors such as activity patterns, dietary composition, and operational conditions.

Taken together, the comparative evidence indicates that while reductions in vitamin D status represent a cross-habitat feature of isolated and confined environments, most other biochemical responses are habitat-specific and appear to be shaped by distinct physiological stressors related to microgravity, immobilization, or environmental conditions rather than isolation per se.

Risk of bias

The risk of bias across the studies included in the review is presented in Fig. 6, and more detailed in the Supplementary Fig. S3. Of the 184 studies assessed, one study was judged to be at critical risk of bias, and 11% were classified as having a serious risk of bias, primarily due to confounding, missing data, or bias in outcome measurement. Only 38% of the studies were rated as having a low overall risk of bias. A moderate risk of bias was most frequently attributed to confounding, accounting for the largest proportion of studies (50%). Accordingly, bias due to confounding emerged as the predominant methodological concern, with most studies exhibiting a

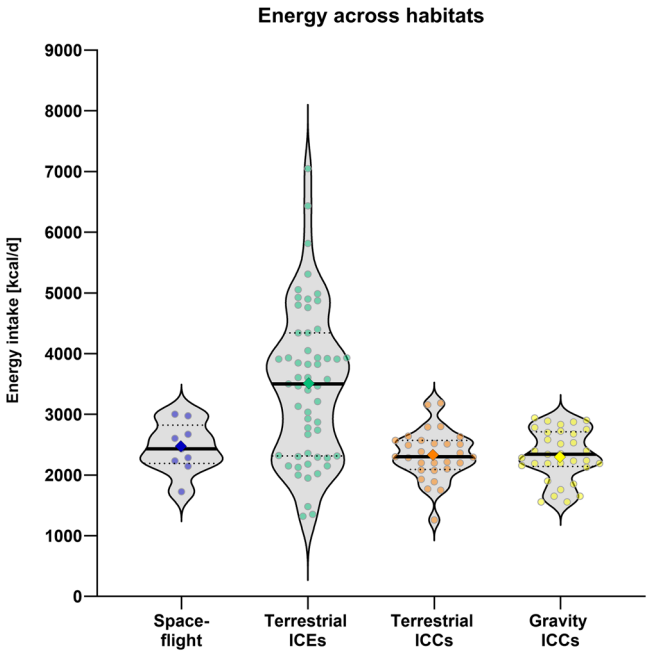


Fig. 2 | Daily energy intake across the habitats. Violin plots showing the distribution of daily energy intake across habitat categories. Each dot represents a single study data point. The width of the violin reflects the density of values. The solid horizontal line within each violin indicates the median, while the dashed lines represent the interquartile range (IQR).

moderate risk and a smaller yet notable subset showing a serious risk in this domain. Despite these limitations, no study was excluded from the review on the basis of risk-of-bias considerations, as the available evidence base in this research field is limited and exclusion would have substantially reduced the scope of the synthesis.

Discussion

Across the four habitat types, dietary provision varied systematically as a function of operational constraints, dietary autonomy, and the degree of experimental control. Spaceflight missions and bed-rest studies constituted the most standardized nutritional environments, characterized by fixed menu cycles, reliance on shelf-stable foods, and predefined energy and macronutrient targets that allowed minimal self-selection. Terrestrial ICC environments occupied an intermediate position, combining tightly controlled dietary protocols in laboratory-based studies with operational supply constraints in applied settings such as submarine missions. In contrast, terrestrial ICE environments were characterized by the lowest degree of dietary control, with food availability largely shaped by resupply logistics, seasonal conditions, and physical workload. Consequently, dietary patterns in these settings ranged from structured station-based meals to predominantly self-selected, ad libitum intake supplemented by energy-dense rations during outdoor expeditions.

This gradient of dietary control was reflected in both total energy intake and macronutrient distributions. Energy intake showed the greatest variability in ad libitum settings and high-workload terrestrial ICE environments, whereas substantially lower variability was observed in spaceflight, bed-rest, and controlled ICC settings. A similar pattern was evident for macronutrient intake: spaceflight and ICC environments clustered around comparable macronutrient profiles, while terrestrial ICE studies consistently exhibited the widest dispersion. Although ICC environments do not encompass the full spectrum of environmental stressors characteristic of terrestrial ICE settings[130], their standardized food systems and controlled intake conditions tend to produce energy and macronutrient profiles that more closely resemble those reported in spaceflight with respect to dietary structure. Accordingly, ICC environments may offer a useful framework for examining nutritional mechanisms and for exploring the transferability of findings from terrestrial analogs to spaceflight[130,131], whereas terrestrial ICE environments may provide further insight into nutritional responses under ecologically valid extreme conditions, albeit with greater variability and more limited feasibility of dietary monitoring.

Macronutrient distributions generally fell within reference ranges but showed context-specific shifts. Carbohydrate intake typically accounted for 40–70% of total energy[132]. Fat intake, however, frequently approached or exceeded upper recommended limits (≤30% of total energy[133]) and increased systematically with rising physical workload, thereby increasing dietary energy density. This pattern was most pronounced in terrestrial ICE studies involving prolonged endurance activities, such as long-distance skiing expeditions[134] or extended sledging journeys in Antarctica[74,75,135,136]. Under such conditions, increased dietary energy density, primarily via higher fat intake, is consistent with the metabolic demands of prolonged moderate-intensity activity, enabling sustained energy provision and supporting the maintenance of energy balance over extended work periods. Protein intake similarly exhibited context-dependent variation, with higher intakes predominantly reported in ICE environments involving sustained outdoor work[137,138]. In these settings, increased protein availability may support the preservation of fat-free mass and contribute indirectly to energy metabolism when carbohydrate availability is constrained. By contrast, bed-rest studies represent a distinct physiological context. Under minimal mechanical loading, even high protein intake did not prevent muscle loss, indicating that protein effectiveness depends on concurrent mechanical stimuli[108,139]. Consistent with this, recent syntheses of microgravity and bed-rest countermeasure research emphasize the necessity of individualized, resistance-based exercise programs to attenuate musculoskeletal deconditioning[130]. Taken together, established dietary requirements should provide the foundation for nutritional planning[5,29,132,133], while allowing targeted, context-specific adaptations as part of integrated countermeasure strategies. In particular, deliberate modulation of dietary energy density emerges as a practical and scalable nutritional countermeasure[140] to support energy balance under conditions of high physical workload, environmental stress, or constrained intake capacity. However, implementing increased energy density primarily through higher fat content carries potential trade-offs, depending on the quality and stability of the fat sources used, as well as reduced food acceptability and palatability fatigue during prolonged missions[141,142]. This strategy is also unlikely to address situations in which food scarcity, rather than insufficient caloric density, constitutes the primary driver of energy deficit, and may therefore be most effective when applied selectively in contexts where caloric density itself is the limiting factor.

Body mass responses broadly paralleled dietary patterns across habitats. Habitat-specific differences in dietary intake were accompanied by changes in body mass, suggesting a tendency toward negative energy balance when energetic demands were not fully met[143]. Weight loss was observed in all environments and was most pronounced in terrestrial ICE settings, where both magnitude and variability were greatest. Across habitats, a subset of studies reported weight maintenance or modest gains (25% spaceflight, 54% terrestrial ICE, 43% terrestrial ICC, 30% bed rest). However, losses clearly outweighed gains: increases were uniformly modest (≤7% of baseline), whereas losses reached −29.1%, indicating a pronounced asymmetry. It should be noted, however, that body mass changes in these environments reflect a combination of factors, not all of which are directly attributable to dietary intake. Fluid redistribution, unloading-induced muscle loss, and thermogenic adaptation may each contribute independently of energy balance. Moreover, while dietary provision appeared sufficient in many settings, it remains difficult to determine from the available data whether observed weight loss during field operations reflects constrained food availability, insufficient intake despite adequate provision, or a combination of both. These interpretive limitations notwithstanding, the cumulative impact of even modest short-term losses may become increasingly relevant during long-duration or deep-space missions, where prolonged unloading and constrained countermeasure capacity may amplify fat-free mass loss.

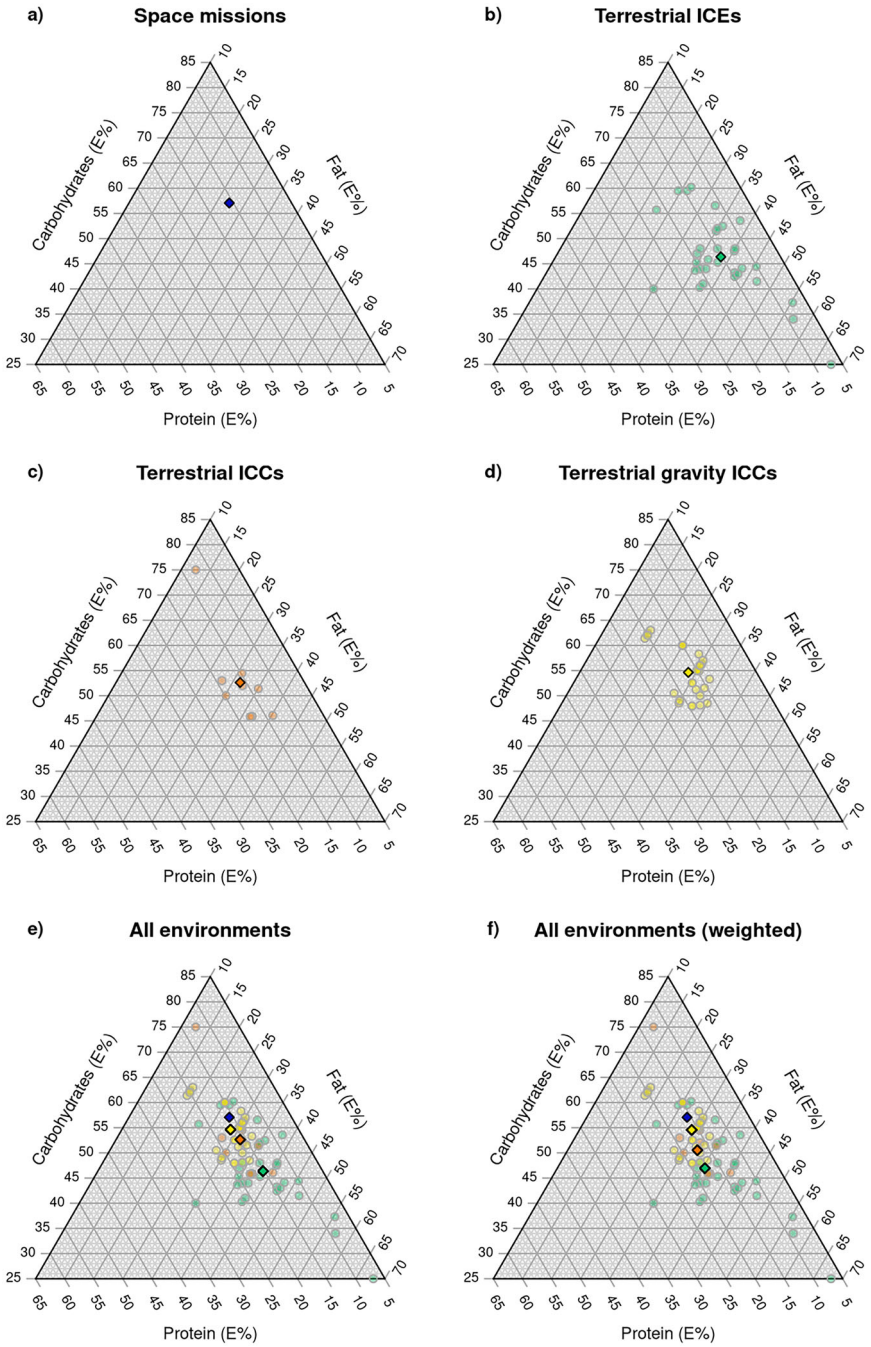


Fig. 3 | Macronutrient distributions across habitats. Ternary plot illustrating the normalized macronutrient distribution (percentage of energy from carbohydrate, fat, and protein) for each individual study (semi-transparent points) and the corresponding habitat-level means (diamond). The plot differentiates four habitat categories: space missions (Group 1, blue), terrestrial ICE environments (Group 2a, green), terrestrial ICC environments (Group 2b, orange), and terrestrial ICC studies reflecting microgravity-like physiological adaptations (Group 2c, yellow). Macronutrient distributions across habitat types: **a** Spaceflight missions; **b** Terrestrial ICE environments; **c** Terrestrial ICC environments; **d** Terrestrial Gravity simulating ICC environments; **e** All environments; **f** All environments with habitat-level means weighted by study sample size.

When examining specific habitats, spaceflight provides a particularly informative example. In spaceflight, weight maintenance or gain was primarily reported in selected ISS missions[71,73]; however, substantial inter-individual variability persisted, with body mass changes ranging from −6.5 to +2.4 kg[71], consistent with historical observations[4]. Part of this variability may reflect the early mission adaptation phase, during which space motion sickness (including nausea and occasional vomiting), transient reductions in energy intake, and fluid shifts commonly contribute to short-term weight loss[5,144]. Beyond these early physiological adaptations, the observed variability also indicates that individual-level determinants of energy balance extend beyond dietary provision alone and likely include psychological factors such as stress, affective responses, and individual coping strategies[145–148]. In one ISS study, stable body mass was accompanied by reductions in fat mass and preservation of lean mass following implementation of a structured exercise program, indicating favorable shifts in body composition rather than net tissue loss[73]. More recent missions also appeared to more closely approach prescribed energy targets, potentially reflecting improvements in appetite regulation as well as enhanced self-monitoring of dietary intake through routine, daily food logging on board the ISS, relative to earlier programs[5].

A different but related pattern emerges in terrestrial ICC and bed-rest analogs. In terrestrial ICC environments, weight maintenance or gain was reported inconsistently, suggesting that mission-specific and individual factors may outweigh exposure duration. Bed-rest studies show a similar pattern, with body mass loss frequently observed despite tightly controlled diets. The initial decline during head-down bed rest is primarily driven by diuresis and fluid redistribution during early adaptation[149,150], leading to rapid losses of body water that are independent of energy intake. Even under energy-balanced conditions, unloading induces early metabolic alterations, including reduced insulin-stimulated glucose disposal and shifts in substrate

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Table 3 | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
1	Agureev et al.[63]	–	The diet followed a 3-d rotating menu with 4 meals/d; 2 formulations were used: an adaptive ration (2484 kcal/d) and an additional supplement set (464 kcal/d; to stabilize appetite, digestion, and energy metabolism during adaptation and re-entry), providing 52 E% CHO, 32 E% Fat, 16 E% Protein	N.R.	N.R.	N.R.	N.R.	Standard in-flight exercise (treadmill, bicycle ergometer, resistance exercise), EE ↑ → ↓	↓
2	Agureev et al.[71]	ISS (Mission 1)	Rations formed from ≈50% Russian and 50% American products, including canned meat/fish/poultry, dairy, vegetables, fruit, cereals, bread, juices, soups, and confectionery; 4 meals/d (some missions shifted to 3), providing 2983 ± 25 kcal/d (53 E% CHO, 31 E% Fat, 16 E% Protein, 28.7 ± 0.2 g/d Fiber)	N.R.	N.R.	Russian Crew: *Aerovit*, American Crew: Vit D Supplement.	N.R.	Regular physical-training program performed; not quantified	↑
		ISS (Mission 2–7)	Rations formed from ≈50% Russian and 50% American products, including canned meat/fish/poultry, dairy, vegetables, fruit, cereals, bread, juices, soups, and confectionery; 4 meals/d (some missions shifted to 3), providing 2815 ± 64 kcal/d (53 E% CHO, 30 E% Fat, 17 E% Protein, 32.1 ± 0.9 g/d Fiber)	N.R.	N.R.	Russian Crew: *Aerovit*, American Crew: Vit D Supplement	N.R.		↓
3	Bychkov et al.[54]	–	6-d rotating menu with ~70 items, original composition: ~80% sterilized foods, ~20% dehydrated foods (reconstituted with hot/cold water), after ~2 months: monotony of largely sterilized foods reported, Revised menu introduced: ~65% dehydrated and ~35% sterilized products, new variant tested onboard and approved by the crew; rations providing ~3300 kcal/d (45 E% CHO, 36 E% Fat, 19 E% Protein)	N.R.	N.R.	*AeroVit* 2×/d	N.R.	N.R.	↓
4	Bychkov et al.[55]	–	Space-station diet of ~65% dehydrated/sterilized foods reconstituted with hot/cold water, 4 meals/d, including meat, dairy, cereals, bread, soups, chocolate and tea, plus limited fresh items (fruit, juices, milk, honey) delivered via Progress/Soyuz; rations providing ~3000 kcal/d (47 E% CHO, 36 E% Fat, 17 E% Protein)	N.R.	N.R.	*AeroVit* 2×/d	N.R.	N.R.	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
5	Drummer et al.[70]		Controlled food intake based on a pre-selected, combined Russian/ American space food menu	1729 ± 195 kcal/d	N.R.	Na: ≈4128.5 mg/d	1.2 ± 0.3 L/d	N.R.	↑/↓
6	Frings-Meuthen et al.[72]	–	Low-Na (2 g/d) and High-Na (5.5 g/d) diet, 5 d in space and 5 d on Earth (6–12 months postflight); nutrients & water constant; planned menu: 50 E% CHO, 31 E % Fat, 17 E% Protein	NR	NR	High vs. Low-sodium diet	N.R.	N.R.	↔
7	Garrett-Bakelman et al.[129]	–	Restricted diet typical for astronauts, matched with exercise countermeasures; planned menu: 50 E% CHO, 31 E% Fat, 17 E% Protein	N.R.	N.R.	Vit D only; no other Vit/mineral supplements during mission.	N.R.	Vigorous exercise (Treadmill, Resistive devices)	↓
8	Gazenko et al.[52]	–	Balanced mixed diet, meals supplied as thermostabilized, freeze-dried, and fresh foods; consumed 3 hot meals/d providing 2900–3000 kcal/d	N.R.	N.R.	N.R.	N.R.	Brief exercise on a bicycle ergometer (5 min at 60 rpm)	↓
9	Gazenko et al.[53]	–	Balanced diet, 6-d rotating menu; ~65% dehydrated foods (freeze-dried), buffet-style ration system, rations providing ~3150 kcal/d (48 E% CHO, 34 E% Fat, 18 E% Protein)	N.R.	N.R.	Water–salt supplements at the end of the flight	1.3–8 L/d	~2 h/d of exercise (bicycle ergometer, treadmill with shock absorbers, expanders)	↓/↔
10	Grigor'ev et al.[56]	–	N.R.	N.R.	N.R.	Water–salt supplements at the end of the flight: Na: ~5175 mg/d, K: ~3441 mg/d, Ca: ~1243 mg/d, Mg: ~462 mg/d		N.R.	N.R.
11	Grigor'ev et al.[58]	–	Standard Salyut-7 space diet; no further dietary details reported	N.R.	N.R.	N.R.	N.R.	N.R.	↓ / ↑
12	Grigoriev and Noskov[64]	–	N.R.	N.R.	N.R.	10% KCl solution with 10 ml/ kg water	N.R.	N.R.	N.R.
13	Grigoriev et al.[57]	–	Space diet composed of ~65% freeze-dried foods and canned items, rations providing ~3000 kcal/d	N.R.	N.R.	Water–salt supplements at the end of the flight	N.R.	Bicycle ergometer, treadmill, G-suit (8 h/d), LBNP, and 3 EVAs (13 h 47 min total; 890–1320 kcal each)	↓
14	Grigoriev et al.[65]	–	Well-balanced diet	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
15	Heer et al.[66]	EuroMIR 94	N.R.	≈1720 ± 270 kcal/d	≈21 E% Protein	Na: ≈4083 ± 1384 mg/d, Ca: ≈776 ± 94 mg/d	≈1.3 ± 0.5 L/d	BMR ~ 2223 kcal/d	↓
		EuroMIR 95	Predefined diet with adequate energy	≈2605 ± 67 kcal/d	≈14 E% Protein	Na: ≈3967 ± 408 mg/d, Ca: ≈739 ± 63 mg/d	≈4.5 ± 0.7 L/d	BMR ~ 2223 kcal/d	↓
16	Larina[69]	–	N.R.	N.R.	N.R.	Na: ↓/↑, K: ↔/↑, Ca: ↓	↓/↔	N.R.	N.R.
17	Leach and Rambaut[45]	–	Controlled diet, repetitive 6-d menu cycle; nutrient-controlled flight food supplied (NASA food system)	N.R.	N.R.	Na: 4669 mg/d → 4439 mg/d; K: 3988 → 3910 mg/d	N.R.	N.R.	↓*

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
18	Leach and Rambaut[46]	Σ	Metabolic-balance diet; repetitive 6-d menu cycle; nutrient intakes controlled within narrow limits	*2897 + 447 kcal/d*	*57 E% CHO, 27 E% Fat, 16 E% Protein;* 90–125 ± 10 g/d Protein	Ca: 750–850 ± 16 mg/d, P: 1500–1700 ± 120 mg/d, Na: 3000–6000 ± 500 mg/d, Mg: 300–400 ± 100 mg/d, K: ≥2740 mg/d	*2.8 + 0.5 L/d*	N.R.	N.R.
19	Leach et al.[47]	–	N.R.	*2897 + 447 kcal/d*	*57 E% CHO,27 E% Fat,16 E% Protein*	*Ca: 894 ± 142 mg/d, P: 1760 ± 267 mg/d, Mg: 310 ± 58 mg/d, Na: 5185 ± 948 mg/d, K: 3854 ± 567 mg/d*	*2.8 + 0.5 L/d*	N.R.	N.R.
20	Oganov et al.[68]	–	Balanced diet with controlled intake; specific countermeasure nutrition plan with salt restriction	N.R.	N.R.	Ca: 700–1200 mg/d	N.R.	Daily exercise: treadmill running, cycling, resistive loading, use of "Penguin" suit	N.R.
21	Rambaut and Johnston[48]	Σ	Diet constant across all phases: 6 individualized menu cycles based on ≈70 food items	*2897 + 447 kcal/d*	*57 E% CHO, 27 E% Fat, 16 E% Protein*	500 IU/d Vit D_2; mineral supplementation (Ca, P, Na, K, Mg) as needed; *Ca: 894 ± 142 mg/d, P: 1760 ± 267 mg/d, Mg: 310 ± 58 mg/d, Na: 5185 ± 948 mg/d, K: 3854 ± 567 mg/d*	*2.8 + 0.5 L/d*	N.R.	N.R.
22	Rambaut et al.[50]	Skylab 2	Controlled diet	2770 + 371 kcal/d	*57 E% CHO, 27 E% Fat, 16 E% Protein*	N.R.	N.R.	Energy utilization: 41.7 → 43.7 kcal/kg/d	↓
		Skylab 3	Controlled diet	3115 + 389 kcal/d		N.R.	N.R.		↓
		Skylab 4	Controlled diet	3281 + 111 kcal/d		N.R.	N.R.		↑
23	Rambaut et al.[49]	–	Diet constant across all phases: 6 individualized menu cycles based on ≈70 food items	N.R.	N.R.	500 IU/d Vit D_2; mineral supplementation (Ca, P, Na, K, mg/d) as needed.	N.R.	N.R.	N.R.
24	Smith et al.[51]	Σ	Skylab food system (~70 thermostabilized/freeze-dried items); repetitive 6-d menu delivering ≥100% NRC nutrients; meals heated (≤69 °C); salt, liquid pepper, garlic & Tabasco provided	3130 ± 488 kcal/d	52 E% CHO, 25 E% Fat, 14 E% Protein; Fiber: 6.2 ± 2.1 g/d	Vit A: 5000 IU/d, Vit D: 500 IU/d, Vit E: 15 IU/d, Thiamine: 10 mg/d, Riboflavin: 10 mg/d, Vit C: 313 mg/d, Niacinamide: 100 mg/d, Vit B6: 15 mg/d, Vit B5: 20 mg/d, Vit B12: 4 µg/d, Folic acid: 35 µg/d, Ca: 913 ± 196 mg/d, P: 1780 ± 332 mg/d, Na: 236 ± 53 mEq/d, K: 98.1 ± 18.6 mEq/d, Cl: 195 ± 44 mEq/d, Fe: 17.2 ± 3.9 mg/d, Zn: 13.1 ± 3.7 mg/d, Cu: 1.64 ± 0.57 mg/d	2.8 ± 0.7 L/d	N.R.	N.R.
25	Smith et al.[1,44]	–	6-d menu cycle, ≈50% Russian and 50% American products; shelf-stable (dehydrated,	<50% of predicted energy requirements	N.R.	Occasional use of multivitamin and mineral supplement.	N.R.	Light cabin work; no countermeasure training	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			thermostabilized, canned); limited fresh foods; no refrigeration						
26	Smith et al.[30]	–	6–10 d menu cycle, ≈50% Russian and 50% American products; thermostabilized, dehydrated, irradiated, intermediate moisture, natural foods; dietitians tailored menus preflight; planned menu: 50 E% CHO, 31 E% Fat, 17 E% Protein	2284 ± 627 kcal/d	≈18 E% Protein	Na: 4556 ± 1492 mg/d, Ca: 1068 ± 384 mg/d, Fe: 23 ± 12 mg/d, Vit D supplements: 10 µg/d (5.7 ± 4.0/wk); multivitamins optional (3.5 ± 2.9/wk)	N.R.	N.R.	↓
27	Smith et al.[73]	Interim Exercise	ISS standard diet with fixed portion sizes, participants encouraged to consume all opened items; planned menu: 50 E % CHO, 31 E% Fat, 17 E% Protein	2234 ± 363 kcal/d	≈15 E% Protein (1.12 ± 0.21 g/kg/d)	Vit D: 800 IU/d; Ca: 912 ± 229 mg/d; Na: 4159 ± 656 mg/d; K: 2980 ± 435 mg/d; Fe: 24 ± 8 mg/d	1.9 ± 0.3 L/d	2.5 h/d training (aerobic + resistive) using elastic bands with limited eccentric load and a narrow-stance exercise set.	↓
		Advanced Exercise	ISS standard diet with fixed portion sizes, participants encouraged to consume all opened items; planned menu: 50 E % CHO, 31 E% Fat, 17 E% Protein	2430 ± 893 kcal/d	≈17 E% Protein (1.39 ± 0.48 g/kg/d)	Vit D: 800 IU/d; Ca: 1025 ± 309 mg/d; Na: 5327 ± 2617 mg/d; K: 3465 ± 1435 mg/d; Fe: 19 ± 6 mg/d	2.2 ± 0.5 L/d	2.5 h/d training with a flywheel system (~90% eccentric load, max 600 lbf) across varied stances and exercises.	↓
28	Stein et al.[67]	–	Ad libitum inflight diet	2145 ± 465 kcal/d	≈18 E% Protein	N.R.	≈94 ± 11% of preflight level	Non-compulsory exercise with variable adherence	↓*
29	Thornton and Ord2,[43]	Skylab 2	Standard Skylab diet	↓	N.R.	N.R.	N.R.	N.R.	↓
		Skylab 3	Standard Skylab diet	↑	N.R.	N.R.	N.R.	N.R.	↓
30	Vorob'ev et al.[59]	–	3–4 meals/d; selection of food items was based on individual astronaut preferences, rations providing ~3000 kcal/d	N.R.	N.R.	N.R.	0.7–0.8 L/d → 1.8–1.9 L/d	Daily treadmill and bicycle-ergometer exercise (2 1/2 h)	↓ / ↑
31	Vorob'ev et al.[60]	–	Standardized 6-d menu with 70 food items; periodic fresh-food resupply via Progress spacecraft, rations providing ~3100 kcal/d (51 E% CHO, 30 E% Fat, 19 E% Protein)	N.R.	N.R.	daily *Aerovit* supplement Water–salt supplements at the end of the flight	1.2–1.7 L/d	60–90 min/d exercise (bicycle ergometer + treadmill)	↓
32	Vorob'ev et al.[61]	–	Standardized 6-d menu (70 items; 4 meals/d): 25 meat items, 5 fish items, 5 cereal items, 10 confectionary items, 12 fruits/juices items, 4 soups, 2 condiments, 6 first courses; periodic fresh-food resupply via Progress; rations providing ~3150 kcal/d (51 E% CHO, 33 E% Fat, 17 E% Protein)	N.R.	N.R.	daily *Aerovit* supplement, Water–salt supplements at the end of the flight	N.R.	1–2×/d cycling + treadmill; cyclic dosing: 3 training days + 1 rest day (optional light gymnastics)	↓ / ↑
33	Vorobyov et al.[62]	30 d-mission	Crew took 4 meals/d; sterilized canned foods; food preserved with silver ions and stored in containers, rations providing ~3000 kcal/d	N.R.	N.R.	Water–salt supplements at the end of the flight	N.R.	30–60 min/d early, 60–120 min/d later, plus treadmill, bike ergometer, and gravity-simulation suit (10–12 h/d)	N.R.
		63 d-mission					0.7–0.8 L/d, → 1.8–1.9 L/d	2x/d exercise (30–45 → 60 min), gravity-simulation suit (10–12 h/	N.R.

Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
								d), and final 4 days with LBNP (30 min 1–2×/d)	
34	Zwart et al.[173]	High Protein/K^+	High APro:K: 4-d high animal protein/K^+ diet (1.0–1.3 g animal protein/mEq K^+); isocaloric, Ca/Na/energy/total protein matched to Low APro:K; crossover (1 High + 1 Low pre-flight, 2 High + 2 Low in-flight); + 1 d uncontrolled "typical intake" (day 30); planned menu: 50 E% CHO, 31 E% Fat, 17 E% Protein	2943 ± 682 kcal/d → 2399 ± 471 kcal/d	1.5 g/kg/d Protein; Fiber: 25 g/d → 21 g/d	Ca: 1515 ± 289 mg/d (→ 1117 ± 177 mg/d), Na: 4525 ± 586 mg/d (→ 4506 ± 575 mg/d); Sulfur 71 ± 12 µg/d (→ 61 ± 8 µg/d), K: 3249 ± 549 mg/d (→ 2810 ± 529 mg/d), all received Vit D 800 IU/d	N.R.	Daily mandatory advanced resistance training + aerobic exercise	↔
		Low Protein/K^+	Low APro:K: 4-d low animal protein/K^+ diet (0.3–0.6 g animal protein/mEq K^+); isocaloric, Ca/Na/energy/total protein matched to High APro:K; same crossover schedule; plus 1-d uncontrolled "typical intake" (day 30); planned menu: 50 E% CHO, 31 E% Fat, 17 E% Protein	2701 ± 457 kcal/d → 3303 ± 651 kcal/d	1.5 g/kg/d Protein; Fiber: 42 g/d → 48 g/d	Ca: 1427 ± 203 mg/d (→ 1240 ± 198 mg/d), Na: 4358 ± 1224 mg/d (→ 3991 ± 943 mg/d); Sulfur 54 ± 6 µg/d (→ 63 ± 11 µg/d), K: 4612 ± 535 mg/d (→ 5046 ± 933 mg/d), all received Vit D 800 IU/d	N.R.	Daily mandatory advanced resistance training + aerobic exercise	↑
Group 2a: terrestrial ICE environments									
35	Acheson et al.[68]	–	All food imported from UK; tinned and dehydrated items + frozen meat 2–3x/week; professional cooks; regular meals (breakfast: cereal + cooked dish, lunch: bread/soup, afternoon snack: cake, dinner: main + dessert)	3210 ± 453 kcal/d	56 E% CHO, 32 E% Fat, 11 E% Protein	N.R.	N.R.	Constant base work duties (scientists, mechanics, cooks, etc.); confined to base area; some recreational travel	N.R.
36	Adams et al.[174]	–	N.R.	≈4800 kcal/d	N.R.	Intramuscular administration of 2 mL Novagran (Vit C: 300 mg, Niacinamide: 100 mg, Thiamine: 5 mg, Riboflavin: 5 mg)	N.R.	Qualitatively described as daily indoor and outdoor work under severe cold conditions; no quantitative measures reported.	N.R.
37	Anton-Solanas[175]	–	N.R.	5815 kcal/d	1.7 g/kg/d Protein	N.R.	N.R.	37.8 km skiing/d (pace: 3.38 km/h), EE: 6000–8000 kcal/d	↓
38	Antonis et al.[176]	Halley Bay, Antarctica	Predominantly canned and dehydrated foods; one fresh meat meal weekly; dehydrated potatoes	3363–3850 kcal/d	47–49 E% CHO, 39–42 E% Fat, 11–14 E% Protein	Vitamin tablets available ad libitum	N.R.	High in summer (sledging and construction work) ↑, low in winter ↓ (due to polar night).	↔
		SANAE Station, Antarctica						High in summer (sledging and construction work) ↑, low in winter ↓ (due to polar night).	↔
39	Belkin and Karasik[82]	–	Standard Soviet Antarctic food ration Food availability: shortage of vegetables and natural juices, ration providing 3124 ± 171 kcal/d (for scientific/admin workers), and 4524 ± 273 kcal/d (for Drivers/Manual workers)	N.R.	N.R.	Synthetic vitamins administered	N.R.	Low (administrative workers) → Medium (scientists) → High (manual workers)	↓
40	Belkin and Karasik[83]	–							↓
41	Bhatia and Pal[177]	–	Regular Indian meals (rice, roti, vegetables, pulses, meat, fish, eggs, milk) and processed foods provided. Perishables stored frozen, leading to potential flavor	N.R.	N.R.	N.R.	N.R.	Overall low; non-convoy mainly indoor tasks, convoy engaged in heavy outdoor work (logistics, machinery, convoys); Calorie intake ↔ expenditure (balanced).	↑

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			and nutrient loss; fresh produce only briefly available in summer						
42	Bhushan et al.[178]	–	Absence of fresh fruits/ vegetables; limited food variety	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
43	Bittel[179]	–	Field rations during expedition ≈4000 kcal/d → ≈4900 kcal/d (last 25 days) with 50–55 E% CHO, 30–55 E% Fat, 10–15 E% Protein	N.R.	N.R	N.R.	N.R.	Sustained daily skiing while hauling ≈50 kg sledge (field); lab tests at rest	↓
44	Boyd[180]	–	Standard ANARE field rations (4700 kcal), on 9 days only half-rations were consumed; otherwise, rations were equally distributed and fully consumed	4050 kcal/d	≈19 E% Protein	N.R.	2.1 L/d + ≈0.5 L/d	Manual labor, driving toboggans, outdoor work (6 h/d average exposure), occasional weather confinement (13 d), EE: 3500 kcal/d	↓
45	Caputo et al.[181]	–	Identical diet for all participants, prepared daily by station chef; wide variety of foods, comparable to European diet.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
46	Case et al.[182]	–	*Normal diet:* Standard station diet; *Energy restriction phases:* 60 h in October and 60 h in August, restricted to Carnation Instant Breakfast with reduced-fat (2%) milk	*Normal diet*: ≈2670 kcal/d *Energy restriction:* 1353 ± 321 kcal/d (Oct), 1321 ± 231 kcal/d (Aug)	N.R.	Station diet ensured ≥150 µg Iodine/d; some individuals received T4 supplementation	Ad libitum	Occupational activities remained unchanged, energy cost and outdoor time varied by job; RMR stable, but decreased after energy restriction	↑
47	Chen et al.[183]	Great Wall Station, Antarctica	Regular resupply ensured continuous access to fresh food, including cereals, meat, vegetables, and fruits	N.R.	N.R.	N.R.	N.R.	*Summer:* 1 h/d outdoor activity *Winter:* ½ h/d outdoor activity	↓*
		Zhongshan Station, Antarctica	No fresh food available during winter (May–December); diet limited to preserved foods (mainly cereals and meat), with shortages in vegetables and fruits	N.R.	N.R.	N.R.	N.R.	*Summer:* 1 h/d outdoor activity *Winter:* 15 min/d outdoor activity	↑
48	Choi et al.[184]	–	Menu-based evaluation of daily meals served at the Antarctic station: Most frequent dishes: "Rice + Soup + 2 side dishes + Kimchi" (53.5%), "Rice + Stew + 2 side dishes + Kimchi" (13.4%). Frequent dish types: grilled foods, pan-fried foods, kimchi, soups, stews, casseroles; fruit and vegetable servings were very limited; fruit mainly canned; lower dietary diversity in winter; Summer rations providing: 1667 ± 225 kcal/ d (57 E% CHO, 24 E% Fat, 19 E% Protein), Winter rations providing: 1671 ± 248 kcal/d (57 E% CHO, 25 E% Fat, 18 E% Protein)	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
49	Cugini et al.[185]	–	3 standardized Meals/d at fixed times	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
50	Easty[186]	–	Plentiful mixed diet mainly of tinned and dehydrated foods;	3363–3850 kcal/d		N.R.	N.R.	Summer: outdoor work, Winter: confined to huts	↑*

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			unrestricted (ad libitum) intake; occasional desire for fresh food reported; no rationing		48 E% CHO, 40 E% Fat, 12 E% Protein				
51	Efimov et al.[187]	–	Two dietary stages: Stage I (start)—800 g/d; Stage II (later stage)—1.0 kg/d. Well-balanced diet included dehydrated meat and dairy products, dry milk, butter, lard, bacon, cereals (buckwheat, oats, potatoes), biscuits, chocolate, sugar, lemons, garlic, tea/coffee, and soups. ~70–75% of protein and fat were of animal origin. 3 meals/d + ad libitum snacks. Food was vacuum-packed for minimal weight and long storage. "Cold lunch" (served as sandwich, 1000 kcal) if cooking was not feasible, rations providing 3400 kcal/d (47 E% CHO, 36 E% Fat, 17 E% Protein; Phase 1) → 4400 kcal/d (40 E% CHO, 44 E% Fat, 16 E% Protein; Phase 2)	N.R.	N.R.	Participants received 2 tablets/d of *Undevit*.	N.R.	Daily 10 h ski travel pulling sledges; air temperature −15 °C to −20 °C; heavy physical workload in drifting-ice conditions, estimated EE ≈ 6000 kcal/d	↓
52	Efremov et al.[188]	–	Diet based on dehydrated food with minimal water and packaging weight (800–3300 g/d, ≈5470 kcal/d, 41 E% CHO, 42 E% Fat, 17 E% Protein). Core foods: dried beef, sublimated cottage cheese, dry milk, butter, pork fat, dry sausage, cereals (buckwheat, wheat), biscuits, chocolate, sugar, and tea/coffee, 2 hot meals/d, (porridge or soup); 1–2 snacks, ration included ~70–75% animal protein/fat, meals prepared with hot water	N.R.	N.R.	Na: 7000 mg/d, K: 4100 mg/d, Ca: 2200 mg/d, Mg: 720 mg/d, P: 3600 mg/d, Fe: 39 mg/d, Vit A: 1.1 mg/d, Vit B_1: 1.9 mg/d, Vit B_2: 3.8 mg/d, Niacin: 21 mg/d, Vit C: 8 mg/d Participants received *Undevit*.	N.R.	Continuous Arctic ski travel with sledges over drifting sea ice; 8–10 h/d at temperatures down to −40 °C. Every 15–20 days a rest day with high-calorie diet (8000–9000 kcal), estimated EE ≈ 6000–7000 kcal/d	↓
53	Farrace et al.[137]	–	Standardized diet	N.R.	40 E% CHO,30 E% Fat,30 E% Protein	N.R.	≥ 1.5 L/d, Ad libitum water	≥8 h/d outdoor manual work (setting up field camp, logistic tasks)	↓
54	Fernández-Riestra[189]	–	*Phase I* (47 days): High-fat, limited fresh produce (provisions only); *Phase II* (49 days): varied diet incl. fresh fruit/vegetables	2294 ± 264 kcal/d (Phase 1) → 2304 ± 233 kcal/d (Phase 2)	*Phase 1:* 38 E% CHO, 41 E% Fat, 21 E% Protein *Phase 2:* 43 E% CHO, 35 E% Fat, 23 E% Protein		N.R.	*Phase I:* strenuous activity (rough seas, constant deck work, high exertion)*Phase II:* less extreme activity after port stop	↔
55	Garshenin[190]	9th, 10th, and 13th Soviet expedition	Standard polar diet during 9th, 10th, and 13th Soviet expedition: canned and concentrated foods, rich in meat and fat, low in dairy, vegetables, fruit	N.R.	N.R.	Ca 550–600 mg/d; Vit C 50–65 mg/d; B-Vits ≈1.5–2.3 mg/d; Vit A ≈ 0.8–1.6 mg/d → below requirement	N.R.	N.R.	N.R.
		17th Soviet expedition		N.R.	N.R.	Fortification: Ca 300 mg/d + daily Vit A: 3 mg, Vit B_1: 5.2 mg, Vit B_2:	N.R.	N.R.	N.R.

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			Standard polar diet during 17th Soviet expedition (same base diet) + fortification from start.			4 mg, Vit B_6 4 mg, Vit C 140 mg, PP (30 mg); later (Sept onward) doses × 1.5 increased			
56	Guenter et al.[191]	–	Exclusively frozen foods; limited variety	N.R.	N.R.	N.R.	N.R.	Work outside in −20 (90 minutes in summer) to −95 °F (5, 15, 30 minutes in winter)	N.R.
57	Gormly[192]	Supplement group	Station diet typical of Australian rations	N.R.	N.R.	Vit C from diet ≈200 mg/d; supplemented +1000 mg/d. Vit C in milk ≈50 mg/L; in canned juice 500–700 mg/L.	≈500–700 mL canned juice/d; other beverages not quantified.	Mixed indoor/outdoor duties; outdoor activity used as a balancing factor between groups.	N.R.
		Non-supplement group	Station diet typical of Australian rations	N.R.	N.R.	Vit C from diet ≈200 mg/d; Vit C in milk ≈50 mg/L; in canned juice 500–700 mg/L.	≈500–700 mL canned juice/d; other beverages not quantified.		N.R.
58	Hicks[193]	–	A wide variety of fresh, frozen, canned, and dehydrated foods was available; Meals were freely chosen	N.R.	Fat ↔	N.R.	N.R.	N.R.	N.R.
59	Iuliano and Ayton[126]	Males	Self-selected ad libitum station diet from bulk-shipped provisions (frozen, canned, dehydrated, limited hydroponic produce). Meals served à la carte. Vegetables: 3.0 ± 2.0 servings/d, Fruit: 2.0 ± 2.1 servings/d, Dairy: 1.1 ± 0.9 servings/d, Meat: 2.9 ± 1.7 servings/d, Grains: 3.0 ± 1.8 servings/d, Extras/ discretionary foods: 6.2 ± 3.6 servings/d	2283 ± 751 kcal/d	43 E% CHO, 33 E% Fat, 19 E% Protein, 6 E% Alcohol, Fiber: 23 ± 10 g/d	Ca: 788 ± 420 mg/d, Fe: 14.8 ± 6.2 mg/d, Mg: 354 ± 147 mg/d, K: 3271 ± 1166 mg/d, Na: 2887 ± 1160 mg/d, Vit D: 125 ± 49 IU/d, Vit C: 146 ± 174 mg/d, Vit A 856 ± 447 µg/d, Thiamin 2.0 ± 1.4 mg/d, Riboflavin 2.4 ± 1.4 mg/d, Niacin 49.5 ± 19.7 mg/d, P: 1714 ± 640 mg/d, Zn: 13.9 ± 6.2 mg/d	N.R.	N.R.	N.R.
		Females	Self-selected ad libitum station diet from bulk-shipped provisions (frozen, canned, dehydrated, limited hydroponic produce). Meals served à la carte. Vegetables: 3.1 ± 2.0 servings/d, Fruit: 2.3 ± 1.8 servings/d, Dairy: 1.0 ± 0.6 servings/d, Meat: 2.6 ± 1.1 servings/d, Grains: 2.4 ± 1.4 servings/d, Extras/ discretionary foods: 5.6 ± 3.0 servings/d	1950 ± 450 kcal/d	44 E% CHO, 35 E% Fat, 17 E% Protein 5 E% Alcohol, Fiber: 22 ± 10 g/d	Ca: 694 ± 207 mg/d, Fe: 11.7 ± 3.5 mg/d, Mg: 296 ± 84 mg/d, K: 2723 ± 726 mg/d, Na: 2312 ± 645 mg/d, Vit D: 106 ± 45 IU/d, Vit C: 93 ± 69 mg/d, Vit A 811 ± 266 µg/d, Thiamin 1.4 ± 0.7 mg/d, Riboflavin 1.6 ± 0.5 mg/d, Niacin 36.0 ± 9.0 mg/d, P: 1364 ± 287 mg/d, Zn: 10.9 ± 3.2 mg/d	N.R.	N.R.	N.R.
60	Iuliano-Burns et al.[194]	25(OH) D > 50 nmol/L	Unfortified diet with negligible Vit D content	2180 ± 93 kcal/d	47 E% CHO, 34 E% Fat, 19 E% Protein	Ca: 759 ± 630 mg/d	N.R.	N.R.	N.R.

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		25(OH)D < 50 nmol/L		2021 ± 111 kcal/d	48 E% CHO, 34 E% Fat, 18 E% Protein	Ca: 741 ± 334 mg/d	N.R.	N.R.	N.R.
61	Iuliano-Burns et al.[195]	12x Supplement	50,000 IU Vit D_3 every month to maintain serum 25(OH)D during total sunlight deprivation	2151 ± 653 kcal/d	44 E% CHO, 36 E% Fat, 20 E% Protein	Ca: 872 ± 574 mg/d, Vit D: 121 ± 51 IU/d	N.R.	N.R.	N.R.
		6x Supplement	50,000 IU Vit D_3 every second month (six doses/year) to test whether less frequent supplementation could sustain Vit D status	2149 ± 661 kcal/d	44 E% CHO, 37 E% Fat, 19 E% Protein	Ca: 740 ± 309 mg/d, Vit D: 135 ± 40 IU/d	N.R.	N.R.	N.R.
		1x Supplement	50,000 IU Vit D_3 dose before departure, serving as the control group to observe the natural decline of Vit D levels during the one-year Antarctic stay	2127 ± 576 kcal/d	41 E% CHO, 38 E% Fat, 21 E% Protein	Ca: 683 ± 368 mg/d, Vit D: 99 ± 45 IU/d	N.R.	N.R.	N.R.
62	Johnsen et al.[134]	–	High-fat, high-calorie freeze-dried expedition diet; energy target: 5058 kcal/d–5931 kcal/d, Additional snacks: 3 kg salami, potato/pork chips	≈4653–5457 kcal/d	*Menu 1:* 27 E% CHO, 66 E% Fat, 8 E% Protein *Menu 2:* 24 E% CHO, 69 E% Fat, 7 E% Protein	N.R.	N.R.	4804 km in 93 days; daily skiing while hauling 180 kg sled, 10–12 h/d; ascent to 3300 m altitude; crossing Priestly Glacier (psychological stress), estimated EE ≈ 6000 kcal/d	↓
63	Junghans et al.[196]	–	Standardized mixed diet (two daily meals at Soviet station), identical menus across test phases; alcohol prohibited; coffee (1–2 cups/d) and cigarettes (2–4/d) allowed	≈38 kcal/kg/d	≈13 E% Protein	N.R.	N.R.	Daily 1.5 km walk to station; limited outdoor work in polar night; one high-load sled trek; RMR 25.1–42.3 kcal/kg/d	↔
64	Klos et al.[26]	–	Meals are prepared daily by professional chefs using mostly shelf-stable, frozen, or canned foods, with limited availability of fresh fruits and vegetables. As the last resupply flight arrives in early February, the availability of fresh items such as fruits, vegetables, eggs, and dairy become limited within weeks, unlike at stations with year-round supply. Ad libitum meal intake with 2 warm and fresh cooked meals/d	1480 ± 500 kcal/d	41.8 E% CHO, 33.8 E% Fat, 20.1 E% Protein, 4.3 E% Alcohol, 10.3 ± 4.3 g/d Fiber	Ca: 537 ± 249.3 mg/d, K: 2345.2 ± 861.4 mg/d, Mg: 226.9 ± 80.5 mg/d, Mn: 2.2 ± 1 mg/d, Na: 1880.5 ± 633.8 mg/d, P: 1042.1 ± 419 mg/d, Fe: 8.8 ± 3.4 mg/d, Zn: 8.4 ± 4.8 mg/d, Cl: 2747.3 ± 951.5 mg/d, Cu: 0.9 ± 0.4 mg/d, I: 107.9 ± 50.3 µg/d, Se: 60.3 ± 26.2 µg/d, Vit A: 729.8 ± 650.1 µg/d, Vit B2: 1.3 ± 0.6 mg/d, Vit B1: 1 ± 0.5 mg/d, Vit B12: 5.5 ± 3.5 µg/d, Vit B6: 1.6 ± 0.9 mg/d, Vit C: 65.4 ± 43.1 mg/d, Vit D: 2.3 ± 1.4 µg/d,	Ad libitum	Standard station activities	↓*

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
						Vit E: 7.8 ± 3.4 mg/d, Folate: 194.5 ± 86.4 µg/d, Niacin: 20.3 ± 10.2 mg/d			
65	Masterton et al.[74]		*Base diet:* The base diet was rich, varied, and ad libitum, with frequent additional meals, snacks, and alcoholic drinks on special occasions; *Sledging diet* (10–19 d): The sledging diet was high in fat and energy, with a large proportion of animal fat (pemmican, butter) and sugars/ carbohydrates from chocolate, sugar, and biscuits. Later, it was slightly extended ad libitum through extra supplies (e.g., chocolate, raisins, milk, biscuits)	*Base hut:* 3911 ± 582 kcal/d, *Sledging:* 4770 ± 167 kcal/d	*Base hut:* 48 E% CHO, 39 E% Fat, 13 E% Protein, *Sledging:* 35 E% CHO, 55 E% Fat, 10 E% Protein	N.R.	N.R.	*Base*: ~8 h sleep, ~11.5 h sitting, ~4.5 h light-to-moderate work, EE: 3581 ± 149 kcal/d; *Sledging*: ~8.7 h sleep, ~6.5 h heavy work, EE: 5198 ± 159 kcal/d	↔
66	Masterton et al.[75]	–	Base diet: normal mixed diet at base hut, Sledging diet (10–19 d): standard sledging ration with liberal extras so that each subject could eat as much as he liked	Base hut: 3911 ± 582 kcal/d, Sledging: 4770 ± 167 kcal/d	≈53–54 E% Fat	N.R.	N.R.	*Base*: variable activities, EE: 3581 kcal/d (3310–3778 kcal/d); *Sledging*: 6–8 h/d sledging or rock scrambling at –20 °C with occasional rest days, EE: 5198 kcal/d (5013–5349 kcal/d)	N.R.
67	Matheson et al.[127]	Dietary Intervention Group - Standard diet	Standard Antarctic station diet based on frozen, canned, and dehydrated foods with limited fresh produce (December–March). Main items included canned fruit, juices, yogurt, frozen meat, fish, and poultry; small quantities of sprouted seeds used for fresh vegetables	2820 ± 538 - 3250 ± 717 kcal/d	36.0–39.9 E% CHO, 36.1–38.2 E% Fat, 11.8–13.6 E% Protein, 3.3–8.3 E% Alcohol, Fiber: 21.3–23.8 g/d	N.R.	N.R.	N.R.	↑
		Dietary Intervention Group - Intervention diet	Standard Antarctic station diet based on frozen, canned, and dehydrated foods with limited fresh produce (December–March). Main items included canned fruit, juices, yogurt, frozen meat, fish, and poultry; small quantities of sprouted seeds used for fresh vegetables. During the intervention (~13 weeks), butter and mixed oils were replaced with canola margarine (~17 g/d) and canola oil (~14 g/d), rich in MUFA (42–63%), n-6 PUFA (12–20%), and n-3 PUFA (6–10%)	3060 ± 645–3203 ± 694 kcal/d	36.9–38.1 E% CHO, 37.1–38.4 E% Fat, 12.8–13.4 E% Protein; Alcohol: 5.0–5.4 E%, Fiber: 22.1–22.9 g/d	N.R.	N.R.	N.R.	↑*
		Non intervention group	N.R.	3920 ± 717 kcal/d	45 E% CHO, 32.7 E% Fat, 16.2 E% Protein; Fiber: 35.2 g/d	N.R.	N.R.	N.R.	↔
68	Milan and Rodahl[197]	Scientist group	Unrestricted self-selected diet from U.S. Navy rations (average 2.1 kg/d = 5944 kcal/d; 11% protein, 41% fat, 48% carbohydrate)	3400–4396 kcal/d	49–54 E% CHO, 33–37 E% Fat, 13–14 E% Protein	N.R.	N.R.	Outdoor activity time 13%/ 3775 kcal/d (March), 6%/ 3370 kcal/d (June), 15%/ 4175 kcal/d (September)	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Navy group		4925 kcal/d	43 E% CHO, 43 E% Fat, 14 E% Protein	N.R.	N.R.	Outdoor activity time 20%; Energy expenditure: 3660 kcal/d	↔
69	Netterstrøm et al.[198]	–	Regular healthy meals, alcohol allowed	N.R.	N.R.	N.R.	N.R.	Moderate occupational physical activity (fishing labor, trawl deck, filleting, machinery)	↔
70	Nieman et al.[199]	–	Pre-portioned foods incl. Nutrient-dense sports bars (providing ~4138 kcal/d to to total energy intake)	7048 kcal/d	45 E% CHO, 44 E% Fat, 13 E% Protein	N.R.	N.R.	Solo trekking 10–12 h/d pulling ~180 kg sled across 1500 km; −20 to −30 °C; severe caloric and physical load.	↓*
71	O'Brien et al.[200]	–	N.R.	2872 ± 543 kcal/d	48 E% CHO, 37 E% Fat, 15 E% Protein	N.R.	2.2 ± 0.6 L/d (week 1–20) → 3.3 ± 0.9 L/d	Outdoor light work: 128 ± 80 mins/d, outdoor heavy work: 44 ± 48 mins/d, Indoor light work: 60 mins/d	↓
72	Okubo[153]	Syowa Station, Antarctica and Traverse, Antarctica	N.R.	Summer: 3027 kcal/d, Winter: 3407 kcal/d	*Summer:* 66 E% CHO, 19 E% Fat, 15 E% Protein, *Winter:* 53 E% CHO, 33 E% Fat, 14 E% Protein	N.R.	N.R.	Summer: 3068 kcal/d (45 kcal/kg/d), Winter: 3181 kcal/d (47 kcal/kg/d); physically more demanding; longer outdoor exposure, higher workload, negative energy balance during traverse	↓
		Syowa Station, Antarctica	N.R.	Summer: 2778 kcal/d Winter: 2738 kcal/d	*Summer:* 57 E% CHO, 29 E% Fat, 14 E% Protein, *Winter:* 62 E% CHO, 20 E% Fat, 18 E% Protein	N.R.	N.R.	Summer: 2555 kcal/d (41 kcal/kg/d), Winter: 2455 kcal/d (37 kcal/kg/d); predominantly sedentary, routine indoor scientific and technical work; very limited physical exertion	↑
73	Oliveri et al.[201]	–	Food shipped from Buenos Aires, unfortified and unsupplemented with Vit D	N.R.	N.R.	Multivitamin supplement containing 100 IU/d (May) or 125 IU/d (July–January) Vit D	N.R.	High; ~30 h/week including scientific duties, maintenance work, and lifting heavy ice blocks.	↓
74	Orr[202]	Hope Bay, Antarctica	Plentiful, mainly canned/dehydrated food, supplemented with fresh seal/penguin meat and frozen beef/mutton, rations providing 3000–4000 kcal/d	N.R.	N.R.	N.R.	N.R.	Year-round, moderate to high (field work, hauling)	↔
		Sledging journey	Standard sledging rations (~24 kg/2 men/10 d), occasionally supplemented with biscuits, chocolate, coffee, or other luxury items; experimental rations heavier (~28 kg) and offered greater variety, Sledging diet: 3900–4100 kcal/d Experimental rations: 5300 kcal/d	N.R.	N.R.	N.R.	1.5–4 L/d	High physical activity level (average 23 km/d sledging)	Standard diet: ↓ Supplemented sledging diet: ↔ Experimental rations: ↔
75	Palinkas et al.[76]	McMurdo Station, Antarctica	3 regular meals/d; standard U.S. Antarctic Program menu	N.R.	N.R.	Iodine ≥ 150 µg/d	N.R.	Routine station duties and outdoor maintenance (~0.25–0.5 h/d)	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Amundson-Scott South Pole Station, Antarctica		N.R.	N.R.	Iodine ≥ 150 µg/d	N.R.	Routine station duties and outdoor maintenance (~0.25–0.5 h/d)	↓*
76	Palinkas et al.[77]	Summer group	N.R.	N.R.	N.R.	Iodine ≥ 150 µg/d, daily supplements: 12 g Tyrosine or 50 µg Levothyroxine + 12.5 µg Liothyronine	N.R.	Operational Antarctic work	↔
		Winter group	N.R.	N.R.	N.R.	Iodine ≥ 150 µg/d, daily supplements: 12 g Tyrosine or 50 µg Levothyroxine + 12.5 µg Liothyronine	N.R.	Operational Antarctic work	↔
77	Parent et al.[203]	–	Freeze-dried, high-energy diet consisting of carbohydrate- and fat-rich foods with added micronutrients; participants also consumed energy bars and hot drinks; identical diet plan for all participants adjusted for EE providing 5800–6500 kcal/d	N.R.	N.R.	N.R.	6 L/d	Daily ski-trekking and sledge-pulling (6–8 h/d, 1400–2200 m altitude)	↓
78	Parker[204]	–	Standard station food prepared by cook; high energy density; self-catering one d/week; ad libitum snacks and alcohol; seasonal overeating mid-winter followed by voluntary dietary restriction ("midwinter feast" → "August dieting")	N.R.	N.R.	N.R.	N.R.	Activity ↓ April–Oct (winter), ↑ Feb–Mar & Nov (summer)	↑/↔
79	Pitson et al.[205]	–	Typical Australian diet, unsupplemented	N.R.	N.R.	Vit D intake from food only (no supplements).	N.R.	Routine station duties (indoors in winter, outdoor work possible in summer)	N.R.
80	Popkin et al.[206]	–	N.R.	≈2000 kcal/d	N.R.	Normal Vit activity in samples analyzed; no functional thiamine deficiency found.	N.R.	N.R.	N.R.
81	Premkumar et al.[14]	–	N.R.	*Summer:* 2927 ± 472 kcal/d, *Winter:* 2320 ± 356 kcal/d	*Summer:* ≈58 E% CHO, 28 E% Fat, 14 E% Protein *Winter:* ≈63 E% CHO, 25 E% Fat, 13 E% Protein	Vit D intake ↑ (due to frozen fish, meat, eggs, milk, and fortified cereals); vegetarian subgroup consumed less Vit D but had similar serum levels. Vit D supplementation (400 IU/day) and calcium carbonate (equivalent to 500 mg elemental calcium) in case of musculoskeletal pain ($n = 4$).	N.R.	Decreased during polar winter (due to limited external work).	↑
82	Reed et al.[138]	–	Standard U.S. Navy diet providing 3000–3500 kcal/d	N.R.	40 E% CHO, 25 E% Fat, 35% Protein	N.R.	N.R.	~4.3 ± 0.7 h/day outdoor exposure; routine base duties, no exercise intervention	↔
83	Reed et al.[207]	–	N.R.	N.R.	N.R.	Iodine intake explicitly stated (150 µg/d); other micronutrients not reported	N.R.	Routine station work; ~0.5 h/day outdoor exposure; no structured exercise program; Resting metabolic rate ↑*	↓
84	Sawhney et al.[208]	–	Diet providing 3500–4000 kcal/d	N.R.	62 E% CHO, 26 E% Fat, 12 E% Protein	N.R.	N.R.	↑ Outdoor manual labor in March/April; ↓ Aug–Dec	↔

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
85	Simpson and Maynard[209]	–	N.R.	2356 kcal/d	N.R.	N.R.	N.R.	Measured via accelerometer; mean ≈10,752 steps/d; activity levels stable across year (9300–12,900 steps/d).	↓*
86	Sletten et al.[210]	–	N.R.	N.R.	N.R.	50% of participants used supplements (mostly Vit D)	N.R.	Station work: 9–12 h/d, some night shifts	N.R.
87	Smith et al.[33]	400 IU/d Supplement	Standard McMurdo Station diet; no Vit D fortification beyond typical U.S. food supply	N.R.	N.R.	Vit D Supplementation: 400 IU/d	N.R.	N.R.	↑
		1000 IU/d Supplement		N.R.	N.R.	Vit D Supplementation: 1000 IU/d	N.R.	N.R.	↔
		2000 IU/d Supplement		N.R.	N.R.	Vit D Supplementation: 2000 IU/d	N.R.	N.R.	↔
		Non-Supplement		N.R.	N.R.	No Vit D Supplementation	N.R.	N.R.	↔
88	Sonnenfeld et al.[211]	–	Primarily fruits and vegetables; deliberately Vit D-depleted	N.R.	N.R.	Vit D excluded; others not specified. Vit D depletion	N.R.	confined to ~9.3 m² habitat, minimal	↓
89	Steinach et al.[212]	–	Mainly frozen and processed foods; limited fresh fruits/vegetables (only Nov–Feb); no caloric restriction; no rationing; Vit D content low	N.R.	N.R.	N.R.	N.R.	Routine station work; outside activity minimized during winter	↓
90	Strewe et al.[162]	Neuymayer Station, Antarctica	Regular day–night rhythm maintained with common meals. Stored supply goods (fridges/freezers)	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
		Concordia Station, Antarctica							
91	Stroud[135]	–	Each man consumed pre-packed daily rations totaling 956 g food/d. Major components: butter, corn oil, biscuits, oatmeal blocks, chocolate, salami, soups, freeze-dried meals, and bacon bars. Butter added to all meals/drinks. Each ration individually weighed and fully consumed	4900 kcal/d	34 E% CHO, 57 E% Fat, 9 E% Protein	Supplemented: multivitamin tablet weekly; freeze-dried meals fortified.	≈3.5 L/d	Daily 8.5 h sledging (man-hauling, on skis), 3 short breaks/d, 1.5–3 h camp preparation; pulling ~155 kg sledges; ambient temperature −10 °C on average (range 0 to −35 °C); Average EE ≈ 6450 kcal/d (Diary-based estimate: 6930 kcal/d; from intake and weight loss: 5980 kcal/d).	↓
92	Stroud et al.[136]	Σ	Ad libitum consumption of freeze-dried, high-fat rations (Be-Well Nutrition, UK): supplemented with butter, chocolate, biscuits, soups,	4760 kcal/d (Phase 1) → 5310 kcal/d (Phase 2)	*Phase 1:* 36 E% CHO, 57 E% Fat, 8 E% Protein	N.R.	N.R.	Endurance walking 10–12 h/d hauling 222 kg sledges over 2300 km and ≈3500 m ascent; EE: 6759.3–9100.0 kcal/d (first 50	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			cereal breakfasts, hot drinks. Optimized for high energy/ weight ratio		*Phase 2:* 39 E% CHO, 54 E% Fat, 7 E% Protein			days), 5708.4–6353.3 kcal/d (last 45 days)	
93	Taylor et al.[78]	Davis Station, Antarctica	Five dietary phases: usual diet (8 wk), low-fat/low-cholesterol/high-fiber diet (12 wk), usual diet (8 wk), repeat low-fat/high-fiber diet (12 wk), and usual diet (8 wk). Overall food quality was high, with varied canned, frozen, and limited fresh items plus small hydroponic produce, comparable to Australian standards.	*Diet 1:* 3576 kcal/d, *Inter-Diet:* 3825 kcal/d, *Diet 2:* 3468 kcal/d, *Post-Diet*: 3930 kcal/d	N.R.	N.R.	N.R.	Mostly sedentary indoor work; some gym-based weight training; limited outdoor activity, BMR: 1772 kcal/d	↔ Intervention: ↓*
		Casey Station, Antarctica	Normal Antarctic station diet; unrestricted intake, no manipulation, on occasions pre-packed composite food products e.g., canned soups, cream biscuits, meat pies	3933 kcal/d	N.R.	N.R.	N.R.	Mainly indoor work during winter; minimal outdoor exposure, BMR: 1744 kcal/d	↔
		Macquarie-Island-Station, Antarctica	Normal Antarctic station diet; unrestricted intake, no manipulation, on occasions pre-packed composite food products, e.g., canned soups, cream biscuits, meat pies	3847 kcal/d	N.R.	N.R.	N.R.	Frequent outdoor hiking; physically active lifestyle compared to Antarctic stations, BMR: 1772 kcal/d	↓
94	Taylor et al.[79]	–	5 dietary phases: 8-week pre-diet ("Typical Australian diet"), 12-week low-fat/low-cholesterol/ high-fiber diet (<30% fat; PUFA: MUFA: SFA = 1:1:1; <300 mg cholesterol; >30 g fiber/d), 8-week inter-diet (usual diet), 12-week Diet 2 (repeat of Diet 1), and 8-week post-diet (usual diet).	*Pre-Intervention:* 3825 kcal/d, *Intervention:* 3468 kcal/d, *Post-Intervention:* 3930 kcal/d	*Pre-Intervention:* 41 E% CHO, 37 E% Fat, 14 E% Protein (Fiber: 22.4 g/d) *Intervention:* 46 E% CHO, 29 E% Fat, 16 E% Protein (Fiber: 33.2 g/d) *Post-Intervention:* 38 E% CHO, 40 E% Fat, 15 E% Protein	N.R.	N.R.	Mostly indoor; moderate recreational and gym activity, BMR: 1772 kcal/d	↔ Intervention: ↓*
95	Taylor et al.[213]	–	6 rotating daily menus; 1009 g/d dry weight; based on endurance-athlete guidelines; Meals: freeze-dried entrées (Extreme Foods), flapjacks, chocolate, nuts, peanut snacks, porridge, soups, milkshakes	4987 ± 25 kcal/d	44 E% CHO, 45 E% Fat, 10 E% Protein	Weekly Multivitamin supplement (Healthspan Gold A–Z)	N.R.	61-d unsupported 1700 km ski traverse, 9–10 h skiing/d, pulling ~80 kg sledges	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
96	Vats et al.[80]	–	During voyage: mostly fresh and some canned foods; at Maitri: mainly packed/canned foods (fruits, jams, milk, yoghurt, cold-stored vegetables, frozen meats, fish, poultry). Alcohol abstention required	3911 ± 310 kcal/d	53 E% CHO, 36 E% Fat, 12 E% Protein	N.R.	N.R.	Activity distribution: 35.1% very light, 16.6% light, 14.3% moderate, 34.0% heavy; EE: 3120 ± 474 kcal/d	↑*
97	Vats et al.[81]	–	Mixed diet primarily of processed and canned foods in Antarctica (canned fruits, fruit juices, frozen meat, poultry, fish, dehydrated items), fresh food mainly available during voyage; none during Antarctic phase	3910 ± 308 kcal/d	N.R.	No vitamin/mineral supplementation.	Ad libitum	Moderate daily expedition work, EE: 3120 ± 474 kcal/d	↑
98	Ventsenostsev[214]	–	High-calorie diet, whole foods	N.R.	N.R.	N.R.	N.R.	N.R.	↔
99	Wilson et al.[215]	–	5–7 bespoke menus (≈50 days total) designed from Antarctic Logistics & Expeditions foods: dehydrated meals, snacks, hot drinks, and energy/recovery powders; macronutrient targets per endurance-athlete recommendations	4872 ± 647 kcal/d (Phase 1) → 4403 ± 836 kcal/d (Phase 2)	52 E% CHO, 35 E% Fat, 13 E% Protein	N.R.	N.R.	Daily ski-hauling (~85 kg sled); 2 rest days (day 21 and 31); activity pattern ↔, EE: 6040 ± 1062 kcal/d	↓
100	Woods et al.[216]	–	UK Ministry of Defence Cold Climate Rations with 10 menu variants, designed to maintain energy balance under cold exposure, providing 6335 ± 149 kcal/d (50–60 E% CHO, 30–37 E% Fat, 7–11 E% Protein)	N.R.	N.R.	N.R.	N.R.	Mixed moderate–vigorous activity, estimated EE: 5783 ± 1690 kcal/d (mid); 5604 ± 1534 kcal/d (end)	↔
101	Yonei et al.[217]	–	Identical rations for all participants, based on frozen food transported from Japan. Vit D mainly from fish, especially salmon; no UV exposure or supplementation	2313 kcal/d	54 E% CHO, 22 E% Fat, 21 E% Protein	Ca: 550.9 mg/d, Vit D: 488 IU/d, No Vit D supplementation	N.R.	Summer step count ↑* vs. winter	↔
102	Zerath et al.[218]	–	Standard French diet; powdered milk imported from France; no reported changes in diet throughout the mission	N.R.	N.R.	No Vit D supplementation; limited dietary Vit D sources (fish rare)	N.R.	5 subjects remained indoor; 10 had limited outdoor exposure (snow-mobile tasks in June–July)	↑*
103	Zhang et al.[219]	Placebo	Identical buffet diet on ship; menu repeated weekly (ad libitum but two staple foods, ≥5 entrées, ≥2–3 fruits/d)	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
		Probiotic		N.R.	N.R.	N.R.	N.R.	N.R.	N.R.
Group 2b: Terrestrial ICC environments									
104	Agureev et al.[87]	–	Fixed 5-meal regimen (breakfast, lunch, dinner, 2 snacks); pre-packaged European foods (Appetito, Kellog, Hipp, Cooppenrath, Enervit); WHO /	↓	N.R.	*Vitrum* multivitamin daily	N.R.	Moderate to high; daily structured training (treadmill, bicycle ergometer, strength training), EE: 1929.6 ± 519.2 kcal/d	↓/↔

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			ISS-standard composition; some participants self-restricted desserts and fat-containing meals, Energy target: 2750 kcal/d (55 E% CHO, 28 E% Fat, 15 E% Protein)						
105	Aufauvre-Poupon et al.[220]	–	2 main meals/d (lunch and dinner), each served in two courses (11–12 am; 7–8 pm), adapted to mission requirements	N.R.	N.R.	N.R.	N.R.	Self-reported (strength, treadmill, ergocycle)	N.R.
106	Barchukov et al.[221]	–	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	↔
107	Chabal et al.[222]	–	Submariners often did not eat regular meals: $n = 3$ 3 meals/d, $n = 51$ 2 meals/d, $n = 4$ 1 meal/d	N.R.	N.R.	N.R.	N.R.	Self-reported exercise ↓*	N.R.
108	Custaud et al.[97]	240 d-mission	The overall design and variety of the food system replicated the diet used by MIR space crews	N.R.	N.R.	One tablet of polyvitamin *Vitrum* administered daily.	N.R.	MIR 4-d cycle (treadmill, ergometer, expanders), EE: 2800 ± 100 kcal/d	↑*
		110 d-mission		N.R.	N.R.		N.R.	Intensive ISS-style training (ergometer, flywheel, strength exercises, simulator); EE: 3500 ± 100 kcal/d	↑
109	Douglas et al.[223]	Standard ISS diet	Standard ISS diet (control): nutritionally complete, shelf-stable foods typical of the current ISS menu, energy target ≈2300 kcal/d	≈2258 kcal/d	39 E% CHO, 40 E% Fat, 18 E% Protein 21.9 g Fiber (*Pre*) → 50 E% CHO, 31 E% Fat, 20 E % Protein 28.8 g Fiber	Ca: 897-933 mg/d, K: 3481–3610 mg/d, Mg: 430–440 mg/d, Mn: 5.3–5.5 mg/d, Na: 2343–2435 mg/d, P: 1754–1803 mg/d, Fe: 19.9–20.8 mg/d, Zn: 13.9–14.7 mg/d, Cu: 1.9–2.0 mg/d, Se: 133–145 µg/d, Vit A: 382–403 µg/d, Vit B2: 2.28–2.34 mg/d, Vit B1: 1.53–1.63 mg/d, Vit B12: 4.7–5.0 µg/d, Vit B6: 2.4–2.5 mg/d, Vit C: 98–108 mg/d, Vit D: 22.9–24.8 µg/d, Vit E: 10.5–11.0 mg/d	2.6–3.0 L/d	N.R.	↓
		Enhanced diet	>6 servings fruits/vegetables/d; >2 flavonoid-rich foods/d; 2–3 serving/wk; >5 tomato-based food/wk, all foods provided by NASA Space Food Systems Lab; no trading allowed, energy target ≈2300 kcal/d	≈2330 kcal/d	40 E% CHO, 39 E% Fat, 18 E% Protein 24.6 g Fiber (*Pre*) → 51 E% CHO, 30 E% Fat, 20 E% Protein 34.2 g Fiber	Ca: 1106–1118 mg/d, K: 4155–4301 mg/d, Mg: 481–486 mg/d, Mn: 5.9–6.0 mg/d, Na: 2274–2399 mg/d, P: 1879–1938 mg/d, Fe: 20.1–21.4 mg/d, Zn: 13.7–14.2 mg/d, Cu: 2.0 mg/d, Se: 145–154 µg/d, Vit A: 448–483 µg/d, Vit B2: 2.4–2.5 mg/d, Vit B1: 1.76–1.83 mg/d, Vit B12: 4.6–4.9 µg/d, Vit B6: 2.5–2.7 mg/d, Vit C: 175–184 mg/d,	2.3–2.6 L/d	N.R.	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
						Vit D: 26.2–26.9 µg/d, Vit E: 12.7–13.2 mg/d			
110	Gasier et al.[128]	Group with Body fat < 25%	Habitual submarine diet (no sunlight, limited exercise facilities, rotating 18-h work-rest cycle). Fruit + vegetable intake (3 ± 1 servings/d), fiber (20 ± 7 g/d), and alcohol intake (1 ± 1 servings/d) all decreased during patrol	2284 ± 675 kcal/d → 2362 ± 911 kcal/d	45 E% CHO, 36 E% Fat, 17 E% Protein → 44 E% CHO, 40 E% Fat, 18 E % Protein	Na: 3785 ± 1239 → 4049 ± 1498 mg/d	N.R.	Rotating 18-h cycle, confined space, limited exercise (mostly light/moderate), PAEE ↔: 953 ± 541 kcal/d ⟶ 932 ± 475 kcal/d	↔
		Group with Body fat > 25%	Habitual submarine diet (no sunlight, limited exercise facilities, rotating 18-h work-rest cycle). Fruit + vegetable intake (4 ± 3 servings/d), fiber (23 ± 9 g/d), and alcohol intake (2 ± 3 servings/d) all decreased during patrol	2790 ± 940 kcal/d ⟶ 2300 ± 900 kcal/d	44 E% CHO, 35 E% Fat, 17 E% Protein → 41 E % CHO, 42 E% Fat, 19 E % Protein	Na: 4269 ± 1473 → 4056 ± 1385 mg/d	N.R.	Rotating 18-h cycle, confined space, limited exercise (mostly light/moderate), PAEE ↔: 1401 ± 538 kcal/d ⟶ 1146 ± 582 kcal/d	↓*
111	Gilman et al.[224]	–	Fresh fruits and vegetables available only during the first two weeks of the patrol; thereafter crew subsisted on stored or processed foods	N.R.	N.R.	Vit C from rations and optional daily Vit supplement (75 mg ascorbic acid per tablet, issued ad libitum)	N.R.	N.R.	N.R.
112	Gilman et al.[225]	–	N.R.	N.R.	N.R.	Vit D_2: 159 ± 356 IU/d → 88 ± 241 IU/d	N.R.	N.R.	N.R.
113	Gunga et al.[226]	–	3 meals/d; food available in excess	N.R.	N.R.	N.R.	1.4 L/d (17.5 ml/kg/d)	Bicycle ergometer training (→fitness maintained), Accelerometer for step count (~1.5 km/d movement).	↑/↓/↔
114	Katchman et al.[227]	–	4-d cyclic menus of either precooked freeze-dehydrated foods or fresh equivalents; all foods consumed at room temperature; identical nutrient content between diets, Energy provided: *Fresh diet:* 2508 ± 10.5 kcal/d, *Frozen diet:* 2518.8 ± 29.9 kcal/d;	2670 kcal/d	*Fresh diet:* 52 E % CHO, 32 E% Fat, 16 E% Protein *Frozen diet:* 52 E % CHO, 32 E% Fat, 16 E% Protein	Na: 4.36 g/d, K: 3.63 g/d, Ca: 0.81 g/d, P: 1.71 g/d, Cl: 9.88 g/d	1.4 L/d, Ad libitum	N.R.	↔
115	Kraft et al.[96]	240 d-mission	Fixed supply of preserved and dehydrated foods with snacks (meat/fish, dairy, soups, fruits, nuts), processed by sterilization/drying; daily vitamin tablet. MIR-style menu with breakfast, lunch, dinner and optional snacks; food reconstituted with hot water or microwaved, portions self-selected and resupplied during docking; providing 2800 kcal/d (240 d-mission) or 3500 kcal/d (110 d-mission)	N.R.	N.R.	Daily Vitamin supplement	N.R.	Treadmill, cycling, resistive training; 3 training + 1 rest d	↑*
		110 d-mission		N.R.	N.R.		N.R.	Treadmill, cycling, resistive training; 5 training + 2 rest days	↔
116	Lamb et al.[228]	–	Each subject received a controlled diet appropriate to his test condition. Diets consisted of either fresh foods, dehydrated foods, or liquid formulas,	N.R.	N.R.	N.R.	N.R.	Minimal; seated/reclining, no structured exercise.	↑/↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			depending on the experimental group						
117	Maillet et al.[92]	–	Diet not strictly standardized; food and drinks stored in freezers; energy target ≈2700–2800 kcal/d	2599 ± 127 kcal/d	50–60 E% CHO, 35–40 E% Fat, 12–17 E% Protein	Na: 4.8 ± 1.4 g/d, K: 3.8 ± 0.7 g/d, Vitamin- and mineral supplements	3.13 ± 0.35 L/d (↓ -0.68 L/d)	2–12 h / confinement period, EE: 3558 ± 160.4 kcal/d (–864 ± 456 kcal/d)	↓*
118	Maillet et al.[93]	–							
119	Milon et al.[94]	–	Mixed diet of fresh, frozen, canned, and dehydrated foods; nutritionally balanced, culturally adapted; menu based on ESA guidelines; energy target ≈2700–2800 kcal/d; 2 hot meals/d; Breakfast, lunch, dinner and snacks provided	≈2630 kcal/d	47 E% CHO, 41 E% Fat, 14 E% Protein	Vit C 167–243 mg/d, Ca 1367 mg/d, P 1409 mg/d, Fe 15 mg/d, Na 4381 mg/d, K 3575 mg/d, Vit A, B1, B2, B6, and Niacin partly below RDA; Vit/mineral tablets available (3–5/week taken).	≈2.7 L/d	Light/moderate daily activity (~16 h/d); no compulsory exercise.	↓
120	Muid et al.[90]	–	Standardized Mars-500 spaceflight diet in accordance with WHO and ISS nutritional standards; 3 diet variants for different mission phases: *Variant 1:* ≈3120 kcal/d (53 E% CHO, 33 E% Fat, 14 E% Protein); *Variant 2:* ≈3170 kcal/d (47 E% CHO, 35 E% Fat, 17 E% Protein); *Variant 3:* ≈3130 kcal/d (54 E% CHO, 32 E% Fat, 14 E% Protein)	N.R.	N.R.	Ω-3 PUFA supplementation (EPA + DHA 3 g/d) during the first 250 days.	N.R.	Structured exercise program: alternating resistance, treadmill, cycle ergometer, and vibration training	N.R.
121	Nichiporuk et al.[88]	–	N.R.	N.R.	N.R.	Rationed NaCl intake: 12 g (d 1–35), 9 g (d 36–70), 12 g (d 71–75), 6 g (d 76–105); two participants deviated in the final phase.	N.R.	Limited movement, low workload; simulated communication delay (autonomy stress); Basal metabolic rate (BMR) 2182 ± 168 → 1923 ± 12 kcal/d (↓ ~12%); BMR/BM stable (≈25 kcal/kg/d)	↓
122	Paglia and Walford[15]	–	Low-fat, nutrient-dense, plant-based diet grown within Biosphere 2; balanced for essential nutrient adequacy	≈1750 kcal/d ⟶ ≈2100 kcal/d	N.R.	N.R.	N.R.	N.R.	↓
123	Reynolds et al.[229]	–	Standard submarine diet; fresh fruit available ≈30 days, vegetables/dairy ≈45 days; increased snacking and caffeine intake; diet changes due to storage limits	N.R.	N.R.	Supplement: Vit A: 8.6 mg, Vit D: 10 µg, Vit C: 150 mg, Thiamine: 10 mg, Riboflavin: 5 mg, Vit B_6: 0.5 mg, Pantothenic acid: 1 mg, Niacinamide: 50 mg, Vit E: 0.5 mg, Vit B_{12}: 2.5 µg, Fe: 15 mg, Ca: 120 mg, Mn: 0.5 mg, Zn: 0.6 mg, Mg: 3 mg	N.R.	Normal submarine duties; no structured exercise; 18-h work/rest cycle	N.R.
124	Richalet et al.[230]	–	3 ad libitum main meals/d with ad libitum snacks and beverages, balanced diet	≈2800 kcal/d at baseline; ↓ −11% (5000 m) ⟶ −55% (8000 m)	N.R.	N.R.	N.R.	Moderate ad libitum activity (~30–90 min daily treadmill/cycle).	↓
125	Rietjens et al.[231]	–	3 meals/d prepared onboard; free access to snacks; no nutritional guidance; dietary supplements permitted ad libitum	3158 ± 786 kcal/d	N.R.	N.R.	N.R.	PAL: 1.54 ± 0.21, EE: 2937 ± 498 kcal/d	↔
126	Rose et al.[232]	–	Ad libitum menu designed to supply ≈60% carbohydrate, 15% protein, 25% fat.; Meals prepared by dietitian; wide variety of	2639 ± 848 kcal/d (3136 ± 557 → 1789 ± 682 kcal/d)	55 E% CHO, 31 E% Fat, 15 E% Protein	Nutritionally adequat	Ad libitum; positive mean fluid balance (+ 297 ± 207 mL/d)	Light–moderate activity with treadmill, bicycle and ladder ergometer; self-paced exercise decreased at higher altitudes,	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			palatable foods; subjects were encouraged to drink sufficiently					estimated EE ~3050 ± 752 kcal/d with ~400 kcal/d deficit; exercise energy ~715 ± 807 kcal/d, declining with altitude.	
127	Sack et al.[233]	–	Standard submarine rations, typical U.S. diet including Vit D fortification; ad libitum intake	N.R.	N.R.	Vit D fortification in diet; experimental oral dose: 50,000 IU Vit D_2 given at d 3, 31, 59	N.R.	Regular submarine duties; not quantified.	N.R.
128	Schlichting et al.[234]	Nutrition group	N.R.	N.R.	N.R.	Vit D 10 mg/d supplement, ad libitum other nutritional supplements.	N.R.	N.R.	N.R.
		Control group	N.R.	N.R.	N.R.	Ad libitum nutritional supplements.	N.R.	N.R.	N.R.
129	Silverstone and Nelson[84]	–	Predominantly vegetarian diet with small amounts of dairy, eggs and goat/chicken meat (pigs discontinued early); most food produced internally (grains, legumes, vegetables, fruits, fish); crew reported sensory adaptation (increased natural sweetness, reduced acceptance of meat).	≈2200 kcal/d (Range: 1789–2491 kcal/d depending on Month)	Protein: 73 g/d (Range: 62–88 g/d), Fat: 32 g/d (Range:21–40 g/d)	Tyr: 2541 mg/d, Phe: 4902 mg/d, Val: 3701 mg/d, Trp: 858 mg/d, Ile: 3154 mg/d, Lysine: 3617 mg/d, Leu: 6835 mg/d, Met + Cys: 1967 mg/d, Threonine: 2562 mg/d, Vit A: 59591 IU/d, Vit D: 3 IU/d, Vit K: 159 µg/d,	N.R.	Heavy physical workload (agriculture, food prep, animal care).	↓
130	Silverstone[86]	–	Primarily vegetarian diet with limited animal products (daily goat milk; weekly meat/eggs), ~81% locally produced food from 86 crops; staples included rice, sweet potato, beets, banana and papaya; domestic animals were pygmy goats and chickens (pigs only in year 1).	2216 kcal/d	74 E% CHO, 13 E% Fat, 13 E% Protein	Vit B2: 2 mg/d, Vit B6: 5 mg/d, Vit B12: 1 µg/d, Biotin: 71 µg/d, Vit C: 489 mg/d, Vit E: 38 IU/d, Vit B1: 3 mg/d, Niacin: 27 mg/d, Folate: 836 µg/d, Pantothenic Acid: 10 mg/d, Ca: 750 mg/d, Mg: 735 mg/d, Na: 412 mg/d, Cu: 2 mg/d, Zn: 11 mg/d, Cr: 176 µg/d, P: 1628 mg/d, K: 6881 mg/d, Fe: 23 mg/d, Mn: 55 mg/d, Se: 70 µg/d	N.R.	Agriculture field work: 25% of crew time, Animal care: 9%, Food preparation: 12%	↓
131	Simmons et al.[235]	–	Standard ISS menu; breakfast replaced by Bars (750 kcal) for 15 days continuously and then intermittently (every third day), ad libitum consumption. Four Bar flavors: Banana Nut, Orange Cranberry (sweet); BBQ Nut, Jalapeño Nut (savory). Macronutrient profile per bar:	Average intake ≈67% of daily caloric requirement across all meal types; caloric deficit ↑ under daily MRB schedule (−64 kcal/d vs. intermittent).	≈53 E% CHO, 28 E% Fat, 19 E% Protein	N.R.	N.R.	N.R.	↓*

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			50–52% CHO, 18–20% protein, 28–30% fat; ~750 kcal each						
132	Smith et al.[95]	60 d-mission	N.R.	*24-h FFQ:* 2511 kcal/d *7-d FFQ:* 2384 kcal/d *Weighed Records:* 2571 kcal/d	*24-h FFQ:* 80.5 g/d Protein *7-d FFQ:* 70.4 g/d Protein *Weighed Records:* 75.8 g/d Protein	*24-h FFQ:* Ca: 910 mg/d, Fe: 19.4 mg/d, Na: 4100 mg/d *7-d FFQ:* Ca: 943 mg/d, Fe: 23.6 mg/d, Na: 3752 mg/d *Weighed Records:* Ca: 1120 mg/d, Fe: 26.7 mg/d, Na: 3890 mg/d	*24-h FFQ:* 1.7 L/d *7-d FFQ:* 1.9 L/d *Weighed Records:* 2.4 L/d	Confined chamber living; routine maintenance tasks; no formal exercise program.	↔
		91 d-mission	N.R.	*24-h FFQ:* 2083 kcal/d *7-d FFQ:* 1770 kcal/d *Weighed Records:* 2199 kcal/d	*24-h FFQ:* 59.4 g/d Protein *7-d FFQ:* 51.8 g/d Protein *Weighed Records:* 58.5 g/d Protein	*24-h FFQ:* Ca: 1052 mg/d, Fe: 21.0 mg/d, Na: 3845 mg/d *7-d FFQ:* Ca: 937 mg/d, Fe: 17.2 mg/d, Na: 2876 mg/d *Weighed Records:* Ca: 1126 mg/d, Fe: 20.1 mg/d, Na: 3332 mg/d	*24-h FFQ:* 2.7 L/d *7-d FFQ:* 2.6 L/d *Weighed Records:* 3.2 L/d	Confined chamber living; routine maintenance tasks; no formal exercise program.	↔
133	Smith et al.[1,44]	60 d-mission	ISS-type 20-d cycle menu; omnivorous, fresh/frozen/thermostabilized foods; energy matched to WHO requirements for moderate activity (1.6–1.7 × BMR), ad libitum intake	2571 ± 102 kcal/d	Protein: 75.8 ± 3.7 g/d	Ca: 1120 ± 112 mg/d; Fe 26.7 ± 4.2 mg/d; Na 3890 ± 330 mg/d	2.4 ± 0.2 L/d	Light daily work, no exercise device	↔
		91 d-mission	20-d cycle menu (50% vegetarian ≙ ≤4 servings meat/week); one 10-d phase entirely regenerative foods; balanced space food system	2199 ± 198 kcal/d	Protein: 58.5 ± 3.2 g/d	Ca: 1126 ± 162 mg/d; Fe 20.1 ± 5.7 mg/d; Na 3332 ± 170 mg/d	3.2 ± 0.5 L/d	No exercise device	↔
134	Strollo et al.[89]	–	Controlled individualized menus (≈200 food items) balanced for constant nutrient intake; only NaCl intake varied (12–9–12–6 g/d schedule). Water ad libitum; caloric drinks limited	N.R.	N.R.	Rationed NaCl intake: 12 g/d (d 1–35), 9 g/d (d 36–70), 12 g/d (d 71–75), 6 g/d (d 76–105)	Ad libitum water; limited caloric beverages	1×/d bicycle ergometer or treadmill (30–60 min); no sweat losses; RMR ↓*	↓
135	Strollo et al.[91]	–	ISS-type diet: standardized menus; water and food were limited; 4 menu variants; average 15.1% protein, 33.4% fat, 51.2% carbohydrate; meal plans included different types of food products, ready or semi-ready for consumption providing ≈2500–3200 kcal/d (51 E% CHO, 33 E% Fat, 15 E% Protein)	N.R.	N.R.	N.R.	Ad libitum water; limited caloric beverages	N.R.	↓*
136	Thornton and Ord[2,43]	–	Standard Skylab diet	N.R.	N.R.	N.R.	N.R.	N.R.	↓ / ↔
137	Titze et al.[236]	–	Controlled omnivorous diet with free choice of food and fluid. Meals prepared from standardized, pre-	3187 ± 463 kcal/d	N.R.	Na: 247.6.4 ± 33.4 mg/d	2.8 ± 0.4 L/d	Fixed schedule: 6–7 h work/d, 30–60 min exercise (ESA "Mir" protocol)	↑

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
			weighed vacuum-packed ready-to-eat rations						
138	Walford et al.[85]	–	Predominantly vegetarian (grains, legumes, vegetables, fruits, nuts), with small amounts of dairy, eggs, meat, fish. ~85% food grown inside; remainder from backup stores. Same food portions for all regardless of body size	1750–2400 kcal/d	76 E% CHO, 12 E% Fat, 12 E% Protein; Fiber: 46.5 ± 9.9 g/d	High nutrient density; daily supplements given; Vit A ≈ 15009.8 µg/d, Vit B6 ≈ 4.16 mg/d, Vit B12 ≈ 0.25 µg/d, Vit C ≈ 426.15 mg/d, Vit E ≈ 21.21 mg/d, Thiamine (B1) ≈ 2.39 mg/d, Folate ≈ 798.48 µg/d, Riboflavin (B2) ≈ 2.11 mg/d, Niacin ≈ 23.86 mg/d, Ca ≈ 665.0 mg/d, Fe ≈ 26.8 mg/d, Mg ≈ 642.6.0 mg/d, P ≈ 1722.0 mg/d, Se ≈ 33.3 µg/d, Zn ≈ 9.72 mg/d	Ad libitum water	Sustained high levels (70–80-h/wk work)	↓
Group 2c: Terrestrial ICC studies reflecting microgravity-like physiological adaptations									
139	Austermann et al.[98]	–	Strictly controlled, individualized menus defined by DRI standards; 3 meals + 1 snack/d (10-d menu cycle), no coffee, tea, or alcohol; energy target: 130% BMR + 10% TEE	2350 ± 130 kcal/d	50 E% CHO, 32 E% Fat, 15 E% Protein	Vit E: 19.5 mg/d, Vit C: 204 mg/d, Ca: 1180 mg/d, P: 1340 mg/d, Na 3620 mg/d, 1 Vit D bolus (100,000 IU) at baseline	35–50 mL/kg/d	None; passive mobilization 1×/d	↔
140	Austermann et al.[99]	Nutrition group	Isocaloric, standardized hospital diet (MEDES kitchen); 3 meals + 1 snack/d; energy target: 130% BMR + 10% TEE; no caffeine or alcohol	N.R.	International bed rest standards.	Daily micronutrient supplement: 741 mg polyphenols + 1.1 g EPA + 1.0 g DHA + 168 mg Vit E + 80 mg Selenium; 100,000 IU Vit D at baseline	N.R.	None; passive joint mobilization 1×/d	↔
		Control group		N.R.	International bed rest standards.	No supplement		None; passive joint mobilization 1×/d	
141	Barbacini et al.[100]	Nutrition group	Standardized controlled MEDES diet	N.R.	↔	Daily micronutrient supplement: 741 mg polyphenols + 1.1 g EPA + 1.0 g DHA + 168 mg Vit E + 80 mg Selenium	N.R.	None (strict bed rest)	N.R.
		Control group		N.R.	↔	No supplement	N.R.	None (strict bed rest)	N.R.
142	Belavý et al.[237]	Control group	3 Meals/d prepared by hospital kitchen; composition per German Nutrition Society guidelines; all meals consumed completely; no snacks or food exchange allowed	N.R.	50–55 E% CHO, 30–35 E% Fat, 15–20 E% Protein	N.R.	2.4 ± 0.3 L/d	None (strict bed rest)	↓
		Exercise group					2.2 ± 0.7 L/d	High-load resistance training (25 sessions, 3×/week)	↓
		Exercise intervention with Vibration					2.9 ± 0.8 L/d	High-load resistance training (25 sessions, 3×/week) + Whole-body Vibration	↓*
143	Beller et al.[105]	Control group	Isocaloric controlled hospital diet with weight-maintenance target	N.R.	N.R.	N.R.	N.R.	None (strict bed rest).	
		Exercise group	Isocaloric controlled hospital diet with weight-maintenance target	N.R.	N.R.	N.R.	N.R.	Resistive + Whole-body Vibration (11 sessions/week; 3–4 exercises per session).	
				N.R.		N.R.	N.R.	None (strict bed rest).	

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Nutrition group	Isocaloric controlled hospital diet with weight-maintenance target + Protein supplementation		1.6 g/kg/d Protein				
144	Bergouignan et al.[28]	Control group	Hospital-controlled Western diet (7-d menu cycle), 3 meals + 1 faculative snack/d; semi–ad libitum (leftovers + extra portions allowed); energy target: RMR (1191 ± 108 kcal/d) × 1.2	≈1850 kcal/d	55 E% CHO, 30 E% Fat, 15 E% Protein	N.R.	N.R.	None (strict bed rest); TEE 1701 ± 187 kcal/d, Activity EE 7.9 ± 5.4 kcal/kg/d	↓*
		Excercise group	Hospital-controlled Western diet (7-d menu cycle), 3 meals + 1 faculative snack/d; semi–ad libitum (leftovers + extra portions allowed); energy target: RMR (1268 ± 96 kcal/d) × 1.2	≈1900 kcal/d		N.R.	N.R.	Supine resistive + aerobic training (≈19 resistance + 29 aerobic sessions); TEE ≈ 2115 ± 273 kcal/d, Activity EE 12.8 ± 4.2 kcal/kg/d	↓*
145	Bilancio et al.[238]	–	6 meals/d; normocaloric diet, energy target: RMR × 1.2	2781 ± 206 → 2194 ± 139 kcal	60 E% CHO, 25 E% Fat, 15 E% Protein	N.R.	N.R.	None (strict bed rest); passive joint mobilization 3×/week	↓
146	Blanc et al.[239]	–	Conventional diet ad libitum	2282 ± 114 kcal/d	51 E% CHO, 36 E% Fat, 19 E% Protein	Na: 3000 mg/d	2.6 ± 0.2 L/d	TEE: 2318 ± 367 kcal/d	↓
147	Bleeker et al.[240]	Controll group	Controlled diet; identical low-fat meals for all subjects on measurement days. No caffeine or alcohol from midnight; no Vit C supplements 24 h prior.	N.R.	N.R.	N.R.	N.R.	None (strict bed rest)	N.R.
		Excercise group		N.R.	N.R.	N.R.	N.R.	Resistive vibration exercise 2×/d (squats, heel/toe raises, kicks)	N.R.
148	Bychkov and Markaryan[115]	Controll group	*Hypokinesia period (49 d)* + *Control period (12 d):* Strictly controlled fresh-food–based diet. *Rehabilitation period (30 d):* Standard diet.	*Hypokinesia:* 2190 kcal/d *Control:* 2874 kcal/d *Rehabilitation:* 3170 kcal/d	*Hypokinesia:* 47 E% CHO, 32 E% Fat, 19 E% Protein *Control:* 52 E% CHO, 26 E% Fat, 16 E% Protein *Rehabilitation:* 55 E% CHO, 31 E% Fat, 15 E% Protein	N.R.	N.R.	None (strict bed rest)	↓
		Nutrition group	Hypokinesia period (49 d) + Control period (12 d): Strictly controlled fresh-food–based. Rehabilitation period (30 d): modified diet with adjusted ingredient ratios (↑animal protein, ↑ PUFA, ↑ mineral salts).		*Hypokinesia:* 47 E% CHO, 32 E% Fat, 19 E% Protein *Control:* 52 E% CHO, 26 E% Fat, 16 E% Protein *Rehabilitation:* 51 E% CHO, 27 E% Fat, 18 E% Protein	High in minerals (K, Ca, P in cottage cheese and dried stoneless apricots)	N.R.	None (strict bed rest)	↓
149	Bychkov et al.[116]	Controll group	Lower-energy natural-foods diet than pre/post	2190 kcal	47 E% CHO, 32 E% Fat, 19 E% Protein	N.R.	N.R.	N.R.	↓
				2190 kcal/d		N.R.	N.R.	N.R.	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Nutrition group	Lower-energy natural-foods diet than pre/post, post diet with adjusted ingredient ratios (↑animal protein, ↑ PUFA, ↑ mineral salts)		47 E% CHO, 32 E% Fat, 19 E% Protein				
150	Bychkov et al.[117]	Controll group	Fresh-food–based diet	≈2400 kcal/d	N.R.	N.R.	N.R.	None (strict bed rest)	↓
		Nutrition group	Fresh-food–based diet	≈2750 kcal/d	97 g/d Protein	N.R.	N.R.	None (strict bed rest)	
		Nutrition and exercise group	Fresh-food–based diet	≈2900 kcal/d	102 g/d Protein	N.R.	N.R.	Exercise with 200 kcal load.	
151	Clement et al.[241]	–	Controlled diet	N.R.	N.R.	Vit A: 1892 ± 1014 µg/d; I: 233 ± 160 µg/d	50 mL/kg/d	None (strict bed rest).	↓/↔
152	Chopard et al.[106]	Controll group	N.R.	N.R.	1.0 g/kg/d Protein	N.R.	N.R.	None (strict bed rest).	N.R.
		Exercise group	N.R.	N.R.	1.0 g/kg/d Protein	N.R.	N.R.	Combined exercise program (aerobic + resistance)	N.R.
		Nutrition group	N.R.	N.R.	1.6 g/kg/d Protein	N.R.	N.R.	Strict bed rest (no exercise).	N.R.
153	Cromwell et al.[122]	Control group	Metabolic-kitchen diet (10-d menu cycle); 3 meals/d; no caffeine, tea, chocolate; mandatory consumption of all served items	1.3 × HB	55 E% CHO, 30 E% Fat, 15 E% Protein	Vit D: 1200 IU/d; Fe: 17.6 mg/d (for low-ferritin subjects)	≥28.5 mL/kg/d	Strict bed rest (no exercise)	N.R.
		Exercise group						6 d/wk alternating aerobic + resistive trainings (≈2 h/d).	
154	Dorfmann et al.[107]	Control group	N.R.	1.1 × RMR	1.0 g/kg/d Protein	Na: 27.6–36.8 mg/kg/d, K: 35.2–43.0 mg/kg/d, Ca: 1000 mg/d, P: 37.2–49.6 mg/kg/d	≤60 mL/kg/d	None (strict bed rest).	↓
		Exercise group	N.R.		1.0 g/kg/d Protein		60–75 mL/kg/d	3–4×/wk LBNP treadmill running/ walking (40 min + 10 min rest); + resistive flywheel training (every 3rd day)	↓
		Nutrition group	N.R.		1.6 g/kg/d Protein		≤60 mL/kg/d	None (strict bed rest)	↓
155	Downs et al.[123]	Controll group	Controlled, individualized, isocaloric diet; 10-d menu cycle; 3 meals/d, no snacks	1.4 × HB	55 E% CHO, 30 E% Fat, 15 E% Protein	N.R.	N.R.	None (strict bed rest), EE: 2532 ± 421 kcal/d	↔
		Excercise group	Controlled, individualized, isocaloric diet; 10-d menu cycle; 3 meals/d, no snacks	1.6 × HB		N.R.	N.R.	3×/week Resistance + 6×/week Aerobic Training; EE: 2866 ± 349 kcal/d	↔
		Excercise and testosterone group	Controlled, individualized, isocaloric diet; 10-d menu cycle; 3 meals/d, no snacks; Testosterone enanthate: 100 mg 1×/2 weeks	1.6 × HB		N.R.	N.R.	3×/week Resistance + 6×/week Aerobic Training; EE: 2851 ± 234 kcal/d	↔
156	Elmann-Larsen and Schmitt[242]	Control group	Standardized, WHO-guideline diet, individually adjusted for body weight	Individually tailored (WHO standard)	Balanced WHO-based distribution (not further specified)	N.R.	Hydration status monitored	None (strict bed rest)	↓
		Exercise group	Standardized, WHO-guideline diet, individually adjusted for body weight			N.R.		Flywheel-based resistance exercise program	↔

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Medication group	Standardized, WHO-guideline diet, individually adjusted for body weight + Pamidronate and Bisphosphonate			N.R.		None (strict bed rest)	↓
157	Fernandez-Gonzalo et al.[243]	Control group	Fixed meal times; individualized caloric provision to maintain body weight	34.8 kcal/kg/d	50–55 E% CHO, 30–35 E% Fat, 12–15 E% Protein	N.R.	N.R.	None (strict bed rest)	N.R.
		Exercise group				N.R.	N.R.	Resistance exercise every 3rd day	N.R.
158	Gharib et al.[244]	LBNP group	Controlled hospital diet; identical menus throughout	N.R.	N.R.	Na (controlled): ≈3220 mg/d, K (controlled): ≈2740 mg/d	N.R.	LBNP sessions 3–6×/d	↓*
		Control group		N.R.	N.R.		N.R.	N.R.	↓*
159	Greenleaf et al.[118]	Control group	17 rotating daily menus of fresh/frozen foods; 2800 kcal/d prescribed	2678 ± 168 kcal/d	62 E% CHO, 18% Fat, 21 E% Protein	Ca: 1300 mg/d, K: 4900 mg/d, Na: 5400 mg/d, P: 1800 mg/d	2.1 ± 0.2 L/d, ad libitum intake of noncaloric beverages	None (strict bed rest); Ø Energy cost: 83 kcal/h	↓
		Isotonic training	17 rotating daily menus of fresh/frozen foods; 3100 kcal/d prescribed	2833 ± 217 kcal/d	63 E% CHO, 18% Fat, 20 E% Protein	Ca: 1300 mg/d, K: 4800 mg/d, Na: 5500 mg/d, P: 1900 mg/d	2.5 ± 0.3 L/d, ad libitum intake of noncaloric beverages	Isotonic cycling: 2 × 30 min/d; Ø Energy cost: 446 kcal/h (rest)	↓
		Isokinetic training	17 rotating daily menus of fresh/frozen foods; 3100 kcal/d prescribed	2890 ± 199 kcal/d	63 E% CHO, 18% Fat, 19 E% Protein	Ca: 1300 mg/d, K: 4800 mg/d, Na: 5600 mg/d, P: 1900 mg/d	2.4 ± 0.3 L/d, ad libitum intake of noncaloric beverages	Isokinetic leg training, 15 min/leg/d, Ø Energy cost: 214 kcal/h (rest)	↔
160	Greenleaf[119]	Control group	17 rotating daily menus of fresh/frozen foods	2678 ± 168 kcal/d	62 E% CHO, 18% Fat, 20 E% Protein	Ca: 1298 ± 75 mg/d, P: 1856 ± 104 mg/d, Na: 5442 ± 495 mg/d	1.6–2.2 L/d	None (strict bed rest)	↓
		Isotonic training		2833 ± 217 kcal/d				Isotonic cycling: 2 × 30 min/d	↓
		Isokinetic training		2890 ± 198 kcal/d				Isokinetic leg training: 2 × 10 min/d	↔
161	Heer et al.[108]	Control group	Controlled isocaloric diet	1557 ± 107 kcal/d	58 E% CHO, 31% Fat, 14 E% Protein	Ca: 889 ± 154 mg/d, K: 2895 ± 583 mg/d, Na: 2388 ± 364 mg/d, P: 877 ± 142 mg/d	N.R.	None (strict bed rest)	↓
		High Protein group	Controlled isocaloric high-protein diet + 0.72 g BCAA/d	1651 ± 124 kcal/d	50 E% CHO, 31% Fat, 22 E% Protein	Ca: 1291 ± 216 mg/d, K: 3234 ± 477 mg/d, Na: 2694 ± 363 mg/d, P: 1228 ± 170 mg/d	N.R.	None (strict bed rest)	↓
162	Inniss et al.[124]	–	Isocaloric diet (100% NASA requirements); no caffeine/cocoa/chocolate/tea/herbal drinks; 7–10-d standardized menus; mixed fresh/frozen/dried/fortified foods; Targets: Ca 1400 mg/d; P 1400 mg/d; Na <3500 mg/d; K 3000–3500 mg/d; fluids 28.5 mL/kg/d; Multivitamins only for 3 subjects; metabolic-kitchen prepared; full consumption required; energy = HB × 1.3	2156 ± 340 kcal/d	56 E% CHO, 31% Fat, 15 E% Protein; Fiber: 21.1 ± 4.4 g/d	Vit A: 1888 ± 408 µg RE, Vit D: 4.8 ± 1.9 µg, Vit E: 12.9 ± 4.9 mg α-TE, Vit K: 304 ± 133 µg, Vit C: 90 ± 34 mg, Thiamin: 1.5 ± 0.4 mg, Riboflavin: 2.4 ± 0.4 mg, Niacin: 25.1 ± 6.1 mg, Pantothenic acid: 5.1 ± 1.0 mg, Vit B6: 2.4 ± 0.4 mg, Folate: 395 ± 64 µg, Vit B12: 9.6 ± 4.4 µg, Ca: 1154 ± 183 mg, P: 1370 ± 251 mg, Mg: 315 ± 69 mg, Fe: 18.6 ± 2.4 mg, Zn: 11.6 ± 2.1 mg, Co: 1.42 ± 0.34 mg,	3.8 ± 0.6 L/d	N.R.	↔

Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
						Se: 141 ± 40 µg, Na: 2997 ± 594 mg, K: 2791 ± 488 mg, Mn: 4.1 ± 0.8 mg.			
163	Iovino et al.[245]	-	Individualized Slovenian diet (6 meals/d; breakfast, lunch, dinner + 3 snacks); Mandatory consumption of all served items	1.2 × RMR	60 E% CHO, 25 E% Fat, 15 E% Protein; Fiber: 30 g/d	N.R.	↔	None; passive joint mobilization 3×/week	↓*
164	Kermorgant et al.[101]	Controll group	Balanced institutional diet; identical across groups (energy and composition not reported); no supplementation	N.R.	N.R.	Standard dietary levels only; no added supplementation.	N.R.	None (strict bed rest)	N.R.
		Treatment group	Standardized MEDES diet + antioxidant cocktai (6 capsules/d)	N.R.	N.R.	Daily micronutrient supplement: 741 mg polyphenols + 1.1 g EPA + 1.0 g DHA + 168 mg Vit E + 80 mg Selenium.	N.R.	None (strict bed rest)	N.R.
165	Lee et al.[125]	Control group	Controlled isocaloric diet; energy intake daily adjusted to maintain body mass ±1 kg	1.4–1.5 × HB	55 E% CHO, 30 E% Fat, 15 E% Protein; Fiber: 25 g/d	Na (controlled): 3500 mg/d, Ca (controlled): 800–1200 mg/d; no supplements.	Ad libitum, no alcohol/caffeine	None (strict bed rest)	↔
		Exercise group						6×/week 40 min LBNP Treadmill exercise + 5 min passive LBNP	↔
166	Lee et al.[109]	Exercise group	3 Meal/d + up to two snacks; alcohol, caffeine & chocolate prohibited	1.1 × RMR + physical-activity EE	1.0 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	60–75 mL/kg/d	2–3×/wk Flywheel resistance, 3–4×/week LBNP treadmill	N.R.
		Control group	3 Meal/d + up to two snacks; alcohol, caffeine & chocolate prohibited	1.1 × RMR	1.0 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	≤60 mL/kg/d	None (strict bed rest)	N.R.
		Nutrition group	3 Meal/d + up to two snacks; alcohol, caffeine & chocolate prohibited	1.1 × RMR	1.6 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	≤60 mL/kg/d	None (strict bed rest)	N.R.
167	Lemoine et al.[110]	Control group	All meals controlled for energy and nutrients	Adjusted to lower RMR	1.0 g/kg/d Protein	Na, K, Ca, P controlled	N.R.	None (strict bed rest)	N.R.
		Exercise group	All meals controlled for energy and nutrients	Adjusted to lower RMR + physical-activity EE	1.0 g/kg/d Protein	Na, K, Ca, P controlled	N.R.	2–3×/wk Flywheel resistance, 3–4×/week LBNP treadmill	N.R.
		Nutrition group	All meals controlled for energy and nutrients	Adjusted to lower RMR	1.6 g/kg/d Protein	Na, K, Ca, P controlled	N.R.	None (strict bed rest)	N.R.
168	Liu et al.[246]	–	Controlled diet; no alcohol, caffeine, or smoking permitted	2600–2800 kcal/d	≈58 E% CHO, 28–29 E% Fat, 13 E% Protein	N.R.	N.R.	None (strict bed rest)	↑

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
169	Morgan et al.[247]	–	Isocaloric, balanced, mixed diet covering daily nutrient requirements	N.R.	N.R.	Vit D_3 supplement: 800 IU/d; 2000 IU/d if 25(OH)D < 50 nmol/L pre-HDBR; no other supplements; diet met RDAs.	N.R.	N.R.	N.R.
170	Noone et al.[102]	Controll group	Balanced diet	1.33 × RMR	65 E% CHO, 35 E% Fat, 1.2 g/kg/d Protein.	Na: 3631.4 ± 396.2 mg/d, Cl: 6539.3 ± 547.8 mg/d, K: 3825.2 ± 359.3 mg/d, Ca: 1175.8 ± 133.6 mg/d, Mg: 374.8 ± 29.8 mg/d, P: 1336.4 ± 142.1 mg/d, Fe: 12.8 ± 1.7 mg/d, Cu: 1.7 ± 0.1 mg/d, Zn: 15.9 ± 1.7 mg/d, F: 1962.8 ± 289.7 µg/d, I: 237.5 ± 121.2 µg/d, Vit A: 1448 ± 603.3 µg/d, Vit B1: 1.8 ± 0.2 mg/d, Vit B2: 2.0 ± 0.2 mg/d, Niacin: 38.0 ± 5.7 mg/d, Vit B5: 6.1 ± 0.7 mg/d, Vit B6: 2.4 ± 0.3 mg/d, Folate: 453.8 ± 93.2 mg/d, Vit B12: 4.3 ± 1.3 µg/d, Vit C: 203.7 ± 47.5 mg/d, Vit D: 2.7 ± 1.4 µg/d, Vit E: 19.4 ± 2.8 mg/d, Biotin: 43.9 ± 5.6 µg/d, Vit K: 339 ± 192.8 µg/d	2.9 ± 0.16 L/d	None (strict bed rest); EE ↓	↓*
		Treatment group	Standardized MEDES diet + antioxidant cocktail, administered as 6 capsules/d: 2 at breakfast, 2 at lunch, 2 at dinner	1.33 × RMR	65 E% CHO, 35 E% Fat, 1.2 g/kg/d Protein	Na: 3631.4 ± 396.2 mg/d, Cl: 6539.3 ± 547.8 mg/d, K: 3825.2 ± 359.3 mg/d, Ca: 1175.8 ± 133.6 mg/d, Mg: 374.8 ± 29.8 mg/d, P: 1336.4 ± 142.1 mg/d, Fe: 12.8 ± 1.7 mg/d, Cu: 1.7 ± 0.1 mg/d, Zn: 15.9 ± 1.7 mg/d, F: 1962.8 ± 289.7 µg/d, I: 237.5 ± 121.2 µg/d, Vit A: 1448 ± 603.3 µg/d, Vit B1: 1.8 ± 0.2 mg/d, Vit B2: 2.0 ± 0.2 mg/d, Niacin: 38.0 ± 5.7 mg/d, Vit B5: 6.1 ± 0.7 mg/d, Vit B6: 2.4 ± 0.3 mg/d, Folate: 453.8 ± 93.2 mg/d, Vit B12: 4.3 ± 1.3 µg/d, Vit C: 203.7 ± 47.5 mg/d, Vit D: 2.7 ± 1.4 µg/d, Vit E: 19.4 ± 2.8 mg/d, Biotin: 43.9 ± 5.6 µg/d, Vit K: 339 ± 192.8 µg/d Daily micronutrient supplement: 741 mg polyphenols + 1.1 g EPA + 1.0 g DHA + 168 mg Vit E + 80 mg Se		None (strict bed rest); EE ↓	↓*

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
171	Rai et al.[248]	–	N.R.	2230 ± 530 kcal/d	N.R.	Ca: 1089 ± 125 mg/d, Na: 2070 mg/d, K: 3128 mg/d	1.2 ± 0.01 L/d	N.R.	N.R.
172	Rejc et al.[249]	–	Standardized, fully supervised diet adjusted to REE; no additional food allowed	1.2 × RMR	60 E% CHO, 25 E% Fat, 15 E% Protein	N.R.	N.R.	None (strict bed rest)	↓*
173	Ritz et al.[120]	–	Controlled, isocaloric diet (35 kcal/kg/d); macronutrient distribution target: 48 E% CHO, 40 E% Fat, 12 E% Protein; no snacks; identical test meals (7 kcal/kg/d) for calorimetry tests	2532 ± 43 → 2237 ± 50 kcal/d	48–49 E% CHO, 34%–36 E% Fat, 16–17 E% Protein	N.R.	Ad libitum mineral water; no other drinks	None (strict bed rest)	↓*
174	Ritz et al.[121]	–	Controlled 3-meal metabolic diet (breakfast, lunch, dinner) providing 34.9 kcal/kg/d; no snacks or extra food allowed	2581 ± 48 → 2127 ± 24 kcal/d	48 E% CHO, 40 E% Fat, 12 E% Protein	N.R.	2.9 ± 0.1 L/d	None (strict bed rest)	↓*
175	Sakowski et al.[250]	–	Participants followed a controlled diet; no medication, caffeine, or alcohol within 12 h, and no heavy meal ≤ 4 h before testing	N.R.	N.R.	K (controlled): 3000–3500 mg/d	N.R.	None (strict bed rest)	N.R.
176	Scheld et al.[171]	–	Isoenergetic diet; standardized 5 Meals/d; identical menus throughout	2724 ± 245 → 2513 ± 73 kcal/d	126 ± 2 g/d → 116 ± 1 g/d Protein ↓	Ca: 1000 mg/day, P: ~1240–1395 mg/d ↔, 25(OH)D: 25–35 nmol/L ↔ (no supplementation)	Ad libitum mineral water	None (strict bed rest)	↑
177	Schneider et al.[111]	Control group	Controlled diet with weight-maintenance target; Alcohol and caffeine prohibited	1.1 × RMR	1.0 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	≤60 mL/kg/d	None (strict bed rest)	↓*
		Exercise group		1.1 × RMR	1.0 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	60–75 mL/kg/d	Aerobic LBNP treadmill (2–4×/week) + resistive flywheel exercise (2–3×/week)	↓*
		Nutrition group		1.1 × RMR	1.6 g/kg/d Protein	Na ≈ 27.6–36.8 mg/kg/d, K ≈ 35.2–43.0 mg/kg/d, Ca ≈ 1000 mg/d, P ≈ 37.2–49.6 mg/kg/d	≤60 mL/kg/d	None (strict bed rest).	↓*
178	Spaak et al.[172]	–	3 controlled Meals/d; Caffeine and smoking prohibited	≈2300–2500 kcal/d	N.R.	N.R.	1.0–1.5 L/d (water)	Strict bed rest; except 2× 30-min cycling tests	↑
179	Stratis et al.[103]	Control group	N.R.	N.R.	N.R.	N.R.	N.R.	None (strict bed rest)	N.R.
		Nutrition group	N.R.	N.R.	N.R.	Supplement: 168 mg Vit E, 80 µg Se, 2.1 g omega-3 FA, 741 mg polyphenols	N.R.	None (strict bed rest)	N.R.
180	Taibbi et al.[251]	Control group	Standardized diet meeting NASA nutrient specifications; All food compulsory	N.R.	N.R.	N.R.	N.R.	None (strict bed rest)	N.R.
		Exercise group		N.R.	N.R.	N.R.	N.R.	6 d/wk integrated resistance and aerobic training	N.R.
181	Trappe et al.[112]	Control group	Controlled diet	1557 ± 59 kcal/d	56 E% CHO, 30 E% Fat, 14 E% Protein	N.R.	N.R.	None (strict bed rest)	↓
			Controlled diet	1651 ± 82 kcal/d		N.R.	N.R.	None (strict bed rest)	↓

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Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Nutrition group			49 E% CHO, 30 E% Fat, 21 E% Protein				
		Exercise group	Controlled diet	1758 ± 198 kcal/d	57 E% CHO, 30 E% Fat, 13 E% Protein	N.R.	N.R.	Flywheel calf press 2–3×/week + LBNP treadmill 2–4×/week	↓
182	Trappe et al.[113]	Control group	Controlled diet	1557 ± 59 kcal/d	56 E% CHO, 30 E% Fat, 14 E% Protein	N.R.	N.R.	None (strict bed rest)	↓
		Nutrition group	Controlled diet	1651 ± 82 kcal/d	49 E% CHO, 30 E% Fat, 21 E% Protein	N.R.	N.R.	None (strict bed rest)	↓
		Exercise group	Controlled diet	1758 ± 198 kcal/d	57 E% CHO, 30 E% Fat, 13 E% Protein	N.R.	N.R.	Supine squat 2–3×/week + LBNP treadmill 2–4×/week	↓
183	Trappe et al.[114]	Control group	Controlled isocaloric diet	≈1.1 × RMR	1.0 g/kg/d Protein	N.R.	N.R.	None (strict bed rest)	N.R.
		Nutrition group	Controlled isocaloric diet	≈1.1 × RMR	1.6 g/kg/d Protein	N.R.	N.R.	None (strict bed rest)	N.R.
		Exercise group	Controlled isocaloric diet	≈1.1 × RMR	1.0 g/kg/d Protein	N.R.	N.R.	Flywheel calf press 2–3×/week + LBNP treadmill 2–4×/week	N.R.
184	Trim et al.[104]	–	Standardized 7-d cyclic menu; 3 Meals/d + snack, identical food types before/during HDBR	2939 ± 278 kcal/d → 2340 ± 208 kcal/d	50 E% CHO, 33 E% Fat, 17 E% Protein	Na 3963 → 3631 mg/d, K 4453 → 4236 mg/d, Ca 1281 → 1176 mg/d, Mg 428 → 378 mg/d, Fe 14 → 14 mg/d, Zn 16 → 16 mg/d, Cu 2.1 → 2.0 mg/d, Vit A 1574 → 1448 µg/d, Vit B1 2.2 → 1.8 mg/d, Vit B2 3.2 → 2.0 mg/d, Niacin 36 → 31 mg/d, Vit B6 2.7 → 2.4 mg/d, Folate 502 → 447 µg/d, Vit B12 3.5 → 4.3 µg/d, Vit C 269 → 203 mg/d, Vit D + 1000 IU supplement/d, Vit E 25 → 26 mg/d, Biotin 43 → 44 µg/d	1.0–1.6 L/d	None (strict bed rest)	↓*
185	Vinci et al.[139]	Conventional diet group	Isocaloric controlled diet, 1.6 g protein/kg/d (BCAA supplement)	1.1 × RMR	≈50 E% CHO, 28 E% Fat, 21 E% Protein	N.R.	N.R.	None (strict bed rest)	↓*
		High protein diet group	Isocaloric controlled diet, 1.1 g protein/kg/d	1.1 × RMR	≈56 E% CHO, 30 E% Fat, 14 E% Protein	N.R.	N.R.	None (strict bed rest)	↓*
186	Zachwieja et al.[252]	Treatment group	Isocaloric mixed diet; controlled metabolic-kitchen meals; constant intake; 50 µg/d T_3; Testosterone enanthate: 75 mg/d × 3 d (loading), then 200 mg/week	N.R.	28–30 E% Fat, ≥1.2 g/kg/d Protein	N.R.	N.R.	Strict 6° bed rest; horizontal shower 15–30 min/d	↓*
				N.R.		N.R.	N.R.		↓

Table 3 (continued) | Diet descriptions, intakes, physical activity, and body mass changes in Space missions (Group 1) and space analogs (Groups 2a–c)

ID	Author, year	Study group	Diet description and dietary targets	Energy intake Ø	Macronutrient distribution Ø	Vitamin and minerals provided Ø	Fluid intake Ø	Physical activity	Δ Body mass
Group 1: Space missions									
		Placebo group	Isocaloric mixed diet; controlled metabolic-kitchen meals; constant intake; 50 µg/d T_3		28–30 E% Fat, ≥1.2 g/kg/d Protein			Strict 6° bed rest; horizontal shower 15–30 min/d	

The table summarizes dietary structure and targets (diet description), reported energy intake, macronutrient distribution, micronutrient provision (vitamins/minerals), fluid intake, physical activity, and relative change in body mass (Δ body mass) across four habitat categories: Group 1, space missions; Group 2a, terrestrial isolated, confined and extreme (ICE) environments; Group 2b, terrestrial isolated, confined and controlled (ICC) environments; and Group 2c, terrestrial ICC studies reflecting microgravity-like physiological adaptations (e.g., head-down bed rest). Where available, data are reported as mean ± SD. Arrows indicate direction of change relative to baseline (↑ increase, ↓ decrease, ↔ no relevant change). If study groups are marked with Σ, values represent combined trends across all reported intervention and/or control groups.

ICE isolated, confined and extreme, *ICC* isolated, confined and controlled, *ISS* International Space Station, *HDBR* head-down bed rest, *d* day(s), *wk* week(s), *mo* month(s), *y* year(s), *N.R.* not reported, *E%* percentage of total energy intake, *CHO* carbohydrates, *Na* sodium, *K* potassium, *Ca* calcium, *Mg* magnesium, *P* phosphorus, *Cl* chloride, *Fe* iron, *Zn* zinc, *Cu* copper, *I* iodine, *Se* selenium, *Vit* vitamin, *IU* international units, *mEq* milliequivalents, *PUFA* polyunsaturated fatty acids, *MUFA* monounsaturated fatty acids, *SFA* saturated fatty acids, *EPA* eicosapentaenoic acid, *DHA* docosahexaenoic acid, *BCAA* branched-chain amino acids, *BMR* basal metabolic rate, *RMR* resting metabolic rate, *REE* resting energy expenditure, *HB* Harris–Benedict equation, *TEE* total energy expenditure, *EE* energy expenditure, *PAEE* physical activity energy expenditure, *PAL* physical activity level, *LBNP* lower body negative pressure, *EVA* extravehicular activity.

*denotes statistical significance as reported in the original publication. Superscript numbers indicate studies that are listed across multiple habitat categories. Gray-shaded, italicized values indicate data derived from sources other than the cited reference. **Units**. Energy intake is reported in kcal/day (unless otherwise specified). Macronutrients are reported as E% and/or g/day or g/kg/day where available. Micronutrients are reported in mg/day, µg/day, IU/day, or mEq/day as stated in the original publication. Fluid intake is reported in L/day or mL/kg/day.

utilization[151]. With prolonged inactivity and without exercise countermeasures, body mass losses increasingly reflect reductions in fat-free mass, as muscle protein and its associated water are lost. This pattern underscores that body mass declines during bed rest are initially fluid-driven but later dominated by unloading-induced muscle atrophy, which cannot be prevented by protein intake alone without concurrent exercise[152].

Terrestrial ICE environments, in turn, highlight the role of contextual influences in shaping the observed interindividual variability in body mass development. Weight maintenance or gain was primarily reported during low-activity overwintering periods with ad libitum food access in station settings, whereas field operations with higher energetic demands were often associated with weight loss[153], consistent with greater summer losses compared with winter[17]. However, modest average gains (0.2–5.7% of predeployment body mass) and larger sample sizes indicate marked interindividual variability. In addition to differences in energy expenditure related to physical activity, cold exposure may contribute via increased thermogenic energy expenditure[154], with the magnitude of this effect likely depending on environmental conditions, clothing, shelter, and individual cold tolerance. Psychosocial and environmental stressors inherent to ICE settings[155–161], including isolation, confinement, circadian disruption, and altered ambient oxygen conditions, may further modulate appetite and metabolism, although these factors were not systematically assessed in the included studies. Their contribution to the observed dietary patterns therefore remains unclear. Operational factors such as structured day–night schedules in some ICE settings may serve as an example of environmental structuring that could counterbalance stressors such as circadian disruption and thereby support more stable eating behavior[26,162]. Importantly, a temporal pattern was also apparent in terrestrial ICE settings, with shorter deployments often associated with more pronounced initial body mass loss, whereas longer overwintering periods tended to show more stable trajectories and, in some cases, partial recovery toward baseline values. Prolonged stays in ICE environments, such as Antarctic winter-overs at Concordia Station, are associated with progressive physiological and behavioral adaptation over time[22], potentially reflecting an initial phase of elevated energetic strain followed by partial adaptation under stable station-based conditions, although alternative explanations cannot be excluded.

These observations suggest that even highly controlled environments do not necessarily prevent body mass loss. Targeted increases in dietary energy density combined with tailored exercise countermeasures may therefore help mitigate negative energy balance and associated fat-free mass loss across spaceflight and related analog environments, provided that food acceptability and long-term cardiometabolic risks are carefully considered. Early adaptation-related changes further complicate linear interpretations of body mass trajectories, underscoring the importance of considering temporal dynamics rather than assuming constant rates of change.

Micronutrient biomarkers require cautious interpretation. Changes in circulating markers do not necessarily reflect dietary adequacy[163]. In unloading or immobilization contexts, biomarker alterations may arise secondary to tissue remodeling and catabolic processes, leading to the release of endogenous stores[164]. Consequently, normal or even elevated concentrations of selected biomarkers do not preclude underlying deficiency[163]. Calcium illustrates this limitation particularly well[163,164]: in spaceflight and head-down bed rest, increases in serum and urinary calcium predominantly reflect unloading-induced skeletal bone resorption rather than calcium intake or absorption. Such elevations therefore represent a physiological consequence of immobilization and cannot be interpreted as markers of adequate dietary supply. As a result, calcium-related biomarkers obtained under unloading conditions are not directly comparable to those from ambulatory or free-living environments.

Vitamin D emerged as the most consistent micronutrient finding. Circulating 25-hydroxyvitamin D concentrations declined in the absence of supplementation across all habitats, whereas increases were observed only in supplemented cohorts. This uniform trajectory reflects shared constraints across isolated and confined environments, including limited ultraviolet exposure, reduced outdoor activity, and reliance on standardized or

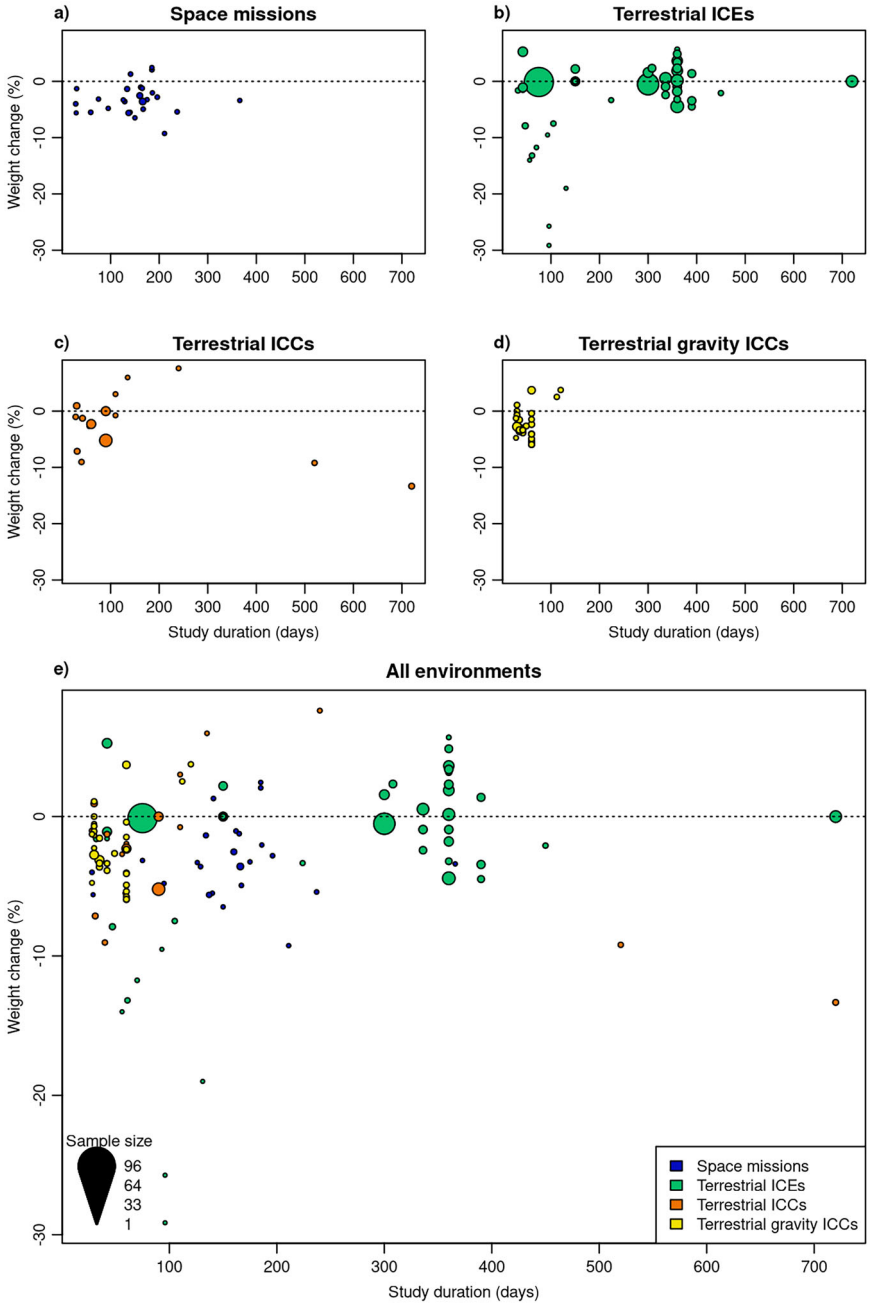


Fig. 4 | Body mass change across habitats. The bubble plot displays the percentage change (%Δ from baseline) of body mass as a function of total study duration (days). Bubble size is proportional to the sample size (*n*) of each study arm, with the minimum and maximum n indicated in the panel. The horizontal dashed line represents zero change relative to baseline (%Δ = 0). Each data point reflects the relative change of body mass from its baseline to its end-of-study value. The plot differentiates four habitat categories: space missions (Group 1, blue), terrestrial ICE environments (Group 2a, green), terrestrial ICC environments (Group 2b, orange), and terrestrial ICC studies reflecting microgravity-like physiological adaptations (Group 2c, yellow). Body mass loss across habitat types **a** Spaceflight missions; **b** Terrestrial ICE environments; **c** Terrestrial ICC environments; **d** Terrestrial Gravity simulating ICC environments; **e** All environments. The following standardization was applied: 1 month = 30 days, 1 year = 12 × 30 days.

monotonous food systems[165]. Unlike other micronutrients, vitamin D status could not be maintained through habitual dietary intake alone. Across the included studies, supplementation doses of up to 2000 IU/day were reported to be well tolerated and effective in maintaining circulating 25(OH)D concentrations within recommended ranges, without evidence of adverse effects[33]. A recent meta-analysis of vitamin D supplementation during Antarctic residence reported a modest but significant pooled increase in 25(OH)D[165]. Although supplementation protocols and baseline vitamin D status varied between studies, the directionality of the response was consistent, underscoring the robustness of this finding. Given the established role of vitamin D in bone metabolism, muscle function, immune regulation, and mood[166–169], the consistent decline observed in non-supplemented settings supports the need for proactive vitamin D strategies in extreme environments. Accordingly, vitamin D supplementation represents an established component of nutritional protocols[5] in spaceflight, and should be considered in ICC and terrestrial ICE contexts[165], accompanied by periodic monitoring of vitamin D status.

Overall, this systematic review has several strengths and limitations. A clear strength is the methodological approach taken according to PRISMA[35] and Cochrane criteria. To achieve a comprehensive overview of the available evidence, a combination of broad search strategies and a highly specific search term set was applied, resulting in the inclusion of 184 eligible studies. Despite clearly defined eligibility criteria, substantial heterogeneity was observed across study designs and reported outcomes. To address this variability, subgroup analyses stratified by environmental setting were conducted, which reduced heterogeneity to some extent and allowed for more context-sensitive interpretation.

Limitations for the interpretation of this review the findings include small sample sizes, limiting statistical power and the scope of quantitative analyses at the individual-study level. Risk of bias was evaluated using the ROBINS-I tool, as recommended by the Cochrane Handbook; the more

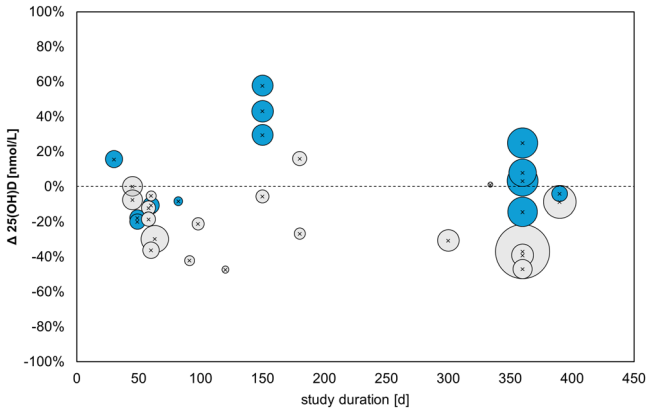


Fig. 5 | Changes (%Δ from baseline) in vitamin D concentrations across study duration and study environments. The bubble plot displays the percentage change (%Δ from baseline) in vitamin D status (25(OH)D) as a function of total study duration (days). Bubble size is proportional to the sample size (*n*) of each study arm, with the minimum and maximum n indicated in the panel. Colors distinguish whether participants received vitamin D supplementation (blue) or no supplementation (gray). The horizontal dashed line represents zero change relative to baseline (%Δ = 0). Each data point reflects the relative change in 25(OH)D from its baseline to its end-of-study value. Where exact pre- or end-of-isolation samples were unavailable, the measurements closest to the start and end of the isolation period were used. The following standardization was applied: 1 month = 30 days, 1 year = 12 × 30 days.

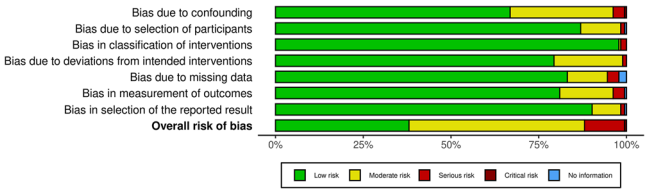


Fig. 6 | Risk of bias assessment.

recently published ROBINS-E tool[170] may represent a closer conceptual fit for observational exposure studies but was not yet available at the time of protocol registration (November 2023). To account for heterogeneity in sample size, participant-weighted analyses were performed alongside unweighted analyses, providing complementary perspectives on cohort-level and study-level trends. Beyond habitat heterogeneity, incomplete reporting, variation in mission duration, and differences in dietary assessment methodologies further constrained direct cross-study comparisons. Further health- and performance-related outcomes were also extracted (Supplementary Table S3), but could not be systematically linked to dietary intake or body-mass changes here, as the primary studies rarely reported these outcomes in direct statistical relation to nutritional data; a meaningful link nonetheless appears plausible and warrants dedicated further investigation. Finally, studies that reported planned dietary provision but did not provide data on actual food intake were excluded from quantitative analyses to avoid conflating prescribed and consumed diets.

In conclusion, maintaining nutritional adequacy in isolated and confined environments remains challenging and insufficiently characterized for longer-duration missions. Because these settings impose unique environmental, physiological, and operational demands, they require integrated, condition-specific nutrition and training strategies. General nutrient recommendations can serve as a useful orientation, but their practical implementation must be adapted to context, for example through higher dietary energy density under elevated workload or environmental stress or through routine vitamin D supplementation in the absence of adequate sunlight. At the same time, the evidence base informing these strategies is still largely derived from low-Earth-orbit and terrestrial analogs, which constrains extrapolation to deep-space missions. As mission duration and distance from Earth increase, nutritional planning becomes progressively more critical, given the reduced resupply options and greater reliance on pre-positioned or stored foods. In such missions, additional factors, including radiation exposure and prolonged storage, may further affect nutrient stability and metabolism, while storage, shelf-life, and mass limitations will likely necessitate continued reliance on prepackaged foods. As a result, key uncertainties persist regarding long-term food-system feasibility, including fatty acid stability, nutrient degradation, and the role of fresh-food production systems such as microgreens. However, while microgreens and other leafy crops have been successfully cultivated on the ISS and may enhance psychological well-being and dietary variety[171], their quantitative contribution to overall nutritional supply remains limited, and space-grown produce can exhibit variability in nutrient content, suggesting that supplementation or biofortification would still be required[172]. Moreover, fresh-food production systems introduce risks beyond nutrient quality: closed cultivation systems carry inherent microbiological risks requiring dedicated food-safety monitoring, and crop yields may not always meet projected requirements, introducing a potential risk of food scarcity that system design alone may not be sufficient to mitigate. More importantly, these crops provide only negligible amounts of energy-dense macronutrients such as fats, and no space-based agricultural system has yet demonstrated the capacity to produce staple, nutrient-dense foods at scales sufficient to meaningfully support overall macronutrient requirements during long-duration missions.

Taken together, these considerations reinforce that maintaining nutritional adequacy in isolated and confined environments remains complex and incompletely characterized, particularly for longer-duration missions. While emerging food-production approaches such as fresh-crop cultivation may complement stored systems, their quantitative contribution to overall energy and macronutrient supply remains uncertain. Therefore, future research should prioritize longitudinal assessments of dietary intake, body mass regulation, and nutrient status under mission-relevant conditions to better define evidence-based nutritional strategies for deep-space exploration.

Data availability

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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Competing interests

The authors declare no competing interests.

Additional information

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