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Closed-Loop Hospitality as a Sustainability Assessment Framework for Space-Analogue Habitats

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Abstract

Closed-loop habitats in space-analogue and other extreme environments must sustain life and performance within tightly bounded constraints on water, energy, food, air revitalisation, waste processing, space, and crew time. Existing assessments emphasise engineering reliability, resource throughput, and human factors, but less often address everyday practices—meals, hygiene, privacy, social rituals, sensory comfort, and care work—as variables relevant to sustainability. This conceptual paper develops closed-loop hospitality as an integrated sustainability assessment framework for analysing how such practices mediate between resource constraints and environmental, social, and operational outcomes. Drawing on sustainability assessment, circular resource use, resilience, socio-technical systems, habitability, and hospitality theory, the framework links constraint variables—including resupply interval, closure ratio, bottlenecks, redundancy, volumetric capacity, crew time scarcity, intercultural crew composition, and health-support capacity—to hospitality design choices and measurable indicators. It identifies outcomes such as resource intensity, recycling and waste burden, system reliability, labour distribution, equity and legitimacy of access, psychosocial wellbeing, compliance, and adaptive resilience. The paper supports threshold setting, scorecards, and protocol design in analogue habitats, arguing that sustainable habitation requires balancing resource stewardship with minimum viable hospitality: preserving dignity, care, privacy, cohesion, and operational continuity within closed-loop limits.

Keywords: sustainable resource utilisation; circular economy; closed-loop life support; sustainability assessment; space-analogue habitats; isolated and confined environments; closed-loop hospitality



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1. Introduction

Sustainable habitation in extreme and closed environments is becoming a critical challenge for both space exploration and terrestrial analogue research. Long-duration habitation beyond Earth intensifies familiar sustainability problems—resource scarcity, waste accumulation, environmental health, social viability, and operational continuity—by placing them within tightly bounded systems with limited resupply and low tolerance for failure. Within sustainability research, assessment frameworks increasingly emphasise that complex systems should be evaluated across multiple dimensions rather than by single efficiency measures, and that meaningful progress depends on clearly defined indicators, explicit system boundaries, and monitoring architectures that inform decision-making [1–3].

Recent work on resilience metrics extends this logic by showing that socio-technical systems require carefully specified variables and justified measures if resilience claims are to be analytically useful rather than rhetorical [4]. In closed habitats, these concerns become especially acute because water, air, energy, food, habitable volume, and waste-processing capacity are tightly coupled, and failures in one domain can quickly propagate through the others [5,6].

Space-analogue habitats provide a particularly useful context for studying these issues because they compress the material, environmental, behavioural, and organisational pressures that future off-Earth habitation will face, while remaining accessible to terrestrial observation and experimentation. NASA human–system guidance treats human factors, habitability, and environmental health as central requirements for human-rated systems, underscoring that sustainable habitation cannot be reduced to life-support engineering alone [7,8]. NASA HERA, NEEMO, and related analogue platforms are designed to simulate isolation, confinement, remote operation, and constrained routines, making them analytically powerful settings for examining the interaction among system constraints, daily practices, and human experience [9,10]. Contemporary reviews of Mars habitation technologies and terrestrial simulation projects similarly show that long-duration settlement depends on closed-loop life support, in situ resource strategies, environmental control, and the management of psychosocial stressors across mission-like settings [11].

At the same time, the literature on space habitation and life-support systems remains focused on engineering performance, operational safety, and physiological or psychological risk, even when it acknowledges the importance of habitability. Reviews of closed ecological and bioregenerative life-support systems show that long-term viability depends on the circulation and recovery of key materials such as water, oxygen, nutrients, and waste streams [5,6,12]. However, many everyday practices through which inhabitants actually live within those systems—how food is organised, cleanliness maintained, privacy protected, social order reinforced, and care expressed—are usually treated as secondary operational details or human-factor considerations, rather than as sustainability-relevant design choices. This creates a conceptual asymmetry: the resource system is scrutinised in detail, while the lived practices through which resources are allocated, experienced, and socially negotiated remain under-theorised.

Hospitality is analytically useful because it identifies this neglected layer of daily life. In hospitality studies, hospitality is not limited to commercial service provision; it has also been theorised as a social and moral practice involving care, comfort, inclusion, relationality, and the management of everyday encounters [13–16]. Humanistic work further links hospitality to dignity and embodied vulnerability, arguing that hospitality concerns how people are received, supported, and enabled to live well, rather than merely served efficiently [17]. In materially closed habitats, apparently soft practices—meal routines, hygiene standards, privacy protocols, communal rituals, and attentiveness to distress—may have significant consequences for resource demand, waste burdens, legitimacy, compliance, cohesion, and resilience.

A clear gap exists in the relevant literature. Sustainability assessment provides tools for integrated evaluation, indicator design, and comparative monitoring, but generally does not operationalise hospitality-related practices as determinants of sustainability performance in closed habitats [1–3,18]. Space-analogue and habitability research offers an indispensable account of confinement, environmental control, and life-support constraints, yet rarely frames hospitality-like practices as a coherent domain of analysis or as a measurable layer of sustainable habitation [7–11]. Hospitality theory introduces concepts of care, comfort, dignity, and social coordination, but rarely addresses hard resource constraints, closed-loop

material systems, or the need for sustainability indicators, thresholds, and monitoring pathways [13–17].

This gap is consequential for both off-Earth and terrestrial sustainable resource utilisation. Closed habitats concentrate sustainability challenges also found at building, neighbourhood, and city scale on Earth, including water reuse, food-waste minimisation, energy conservation, and equitable access to environmental quality (cf. SDG 6, 11, and 12). Lessons developed in analogue habitats, where every litre of water and every gram of waste is traceable to specific practices, can inform broader research on circular resource governance in constrained terrestrial settings such as remote stations, expeditionary healthcare, and high-performance buildings.

This paper addresses this gap by developing the concept of closed-loop hospitality as a sustainability assessment framework for space-analogue habitats. It considers the following three research questions: RQ1: which closed-loop constraint variables shape hospitality-related practices in space-analogue habitats? RQ2: how do hospitality design choices mediate environmental, social, and operational sustainability outcomes? RQ3: which indicators can support the monitoring and comparison of closed-loop hospitality performance across analogue settings? The central contribution is a conceptual framework that repositions hospitality as a resource-governance layer within sustainable habitation, linking daily practices to measurable outcomes in resource intensity, waste burden, wellbeing, legitimacy, labour distribution, compliance, and resilience.

The framework is intended to benefit several stakeholder groups. For space agencies and analogue mission operators, it provides a vocabulary for incorporating daily routines, care work, privacy, hygiene, food, and social rituals into sustainability assessment and protocol design. For habitat designers, life-support engineers, behavioural-health researchers, and crew-support teams, it links material constraints to measurable environmental, social, and operational outcomes. For hospitality, circular economy, and sustainability scholars, it contributes to an emerging body of knowledge on resource-constrained hospitality, circular resource governance, and humane habitation under closure. For terrestrial practitioners—including remote-station managers, expeditionary healthcare planners, emergency-shelter operators, high-performance-building managers, and funders—it identifies transferable indicators for balancing resource stewardship with dignity, wellbeing, and operational continuity.

The remainder of the paper is structured as follows. Section 2 explains the conceptual framework development approach. Section 3 reviews sustainability assessment, circular resource utilisation, life-support systems, space-analogue habitability, psychosocial wellbeing, resilience, and hospitality theory. Section 4 develops the closed-loop hospitality framework and specifies its boundary, functional unit, definitions, and feedback logic. Section 5 operationalises the framework through a monitoring architecture and a set of empirically testable propositions. Section 6 discusses contributions, limitations, and future directions; Section 7 concludes.

2. Conceptual Framework Development Approach

This manuscript is presented as a concept paper rather than a systematic review or empirical study. Its aim is to synthesise several bodies of literature that are typically considered separately and to translate them into an assessment architecture for future empirical research. The framework was developed through a narrative conceptual synthesis of scholarship on sustainability assessment, circular economy indicators, closed-loop life support, space-analogue habitability, isolated and confined environments, resilience, human factors, and hospitality theory.

The literature boundary was defined by the problem rather than by a single disciplinary database. Sources were selected for their foundational concepts, recent reviews, standards, analogue evidence, or measurement instruments relevant to the framework. Sustainability assessment sources were used to define the need for multi-dimensional evaluation, explicit boundaries, and indicators [1–3,18]. Circular economy indicator studies clarified how closure, reuse, and recovery can be measured without equating circularity fully with sustainability [19–21]. NASA standards and life-support documents anchored the resource and habitability constraints in spaceflight-relevant practice [7,8,22]. Space-analogue, psychosocial, and team-dynamics sources framed isolation, confinement, privacy, cohesion, workload, and adaptation as measurable challenges [10,23–26]. Hospitality sources were used to theorise care, dignity, comfort, welcome, and everyday coordination [13–17].

The synthesis proceeded in four steps. First, constraint variables were extracted from the life-support, analogue, and habitability literatures: resupply interval, closure ratio, processing bottlenecks, redundancy, volumetric capacity, environmental stress load, and crew-time scarcity. Second, hospitality-related practices were identified from hospitality theory and from daily-routine concerns common to analogue habitats: meal design, hygiene, privacy, rituals, sensory comfort, care, and service labour. Third, sustainability outcomes were mapped across environmental, social, and operational dimensions. Fourth, candidate indicators were identified to translate the conceptual framework into future monitoring, threshold setting, and comparative evaluation.

The approach has two deliberate limitations. It does not claim to exhaust all relevant literature, and it does not validate a new scale. Instead, it provides a defensible conceptual architecture to guide subsequent analogue studies, quasi-experiments, dashboard design, and scorecard development. This limitation is important because constructs such as dignity, legitimacy, and minimum viable hospitality are conceptually rich and require empirical refinement before they can be treated as validated measures.

3. Literature Review and Theoretical Background

This section synthesises the scholarship most directly relevant to the proposed framework. Rather than reviewing adjacent literatures separately, it traces how sustainability assessment, resource utilisation, closed-loop habitat studies, resilience thinking, human factors research, psychosocial wellbeing, and hospitality theory collectively illuminate the problem of sustaining humane daily life under severe material constraints.

3.1. Sustainability Assessment and Circular Resource Utilisation

The sustainability literature offers the broadest conceptual starting point, as it frames resources beyond a purely technical optimisation problem, focusing on the integrated issues of environmental, social, and economic or operational performance. Sala et al. define sustainability assessment as a structured approach that goes beyond narrow technical evaluation and supports decision-making across domains [1]. Waas et al. similarly position sustainability assessment and indicators as decision-support tools rather than passive reporting devices [2]. Ramos further shows that indicators shape what becomes visible, comparable, and governable in sustainability practice [3]. Ness et al. provide a complementary taxonomy of sustainability assessment tools, highlighting the importance of selecting instruments aligned with the system boundary and decision context [18].

Circular economy research adds specificity to the resource-utilisation aspect of this argument. Geissdoerfer et al. distinguish the circular economy from sustainability, showing that circular strategies can support sustainability but do not automatically achieve it [19]. Indicator reviews by Moraga et al. and Saidani et al. show that circular metrics

vary substantially in what they measure, including recirculation, lifespan extension, recovery, resource productivity, and scale [20,21]. These insights are important for closed-loop habitats because a high closure ratio may reduce external resupply but still generate unacceptable crew-time burdens, hygiene trade-offs, stress, or inequitable labour distributions. Circularity is therefore necessary but insufficient as a sustainability criterion.

In this paper, the circular economy link is operational rather than merely metaphorical. Closed-loop and partially closed analogue habitats can serve as small-scale circular economy testbeds when resource flows are bounded, measured, and tied to specific routines rather than only described at mission scale. Water reuse is affected by hygiene protocols, laundry or wipe-based cleaning, plant or galley practices, and sanitation thresholds. Food circularity is influenced by menu design, portioning, crew acceptability, storage constraints, edible biomass use, and food-waste separation. Material circularity depends on repair, reuse, modular replacement, packaging reduction, consumables management, and the amount of crew time needed to keep loops functioning. Waste circularity is shaped by sorting rules, odour and hygiene control, storage volume, processing bottlenecks, and the perceived legitimacy of waste-related labour. These examples show why analogue habitats are useful for circular economy research: they reveal whether loops can be technically closed and whether circular routines remain acceptable, equitable, and operationally sustainable when enacted by people over time [19–21].

3.2. Closed-Loop Life Support and Space-Analogue Habitability

Closed-loop habitat research provides the material and operational context in which the paper's argument is most evident. Long-duration human presence beyond Earth depends on the regeneration of oxygen, water, and food, and on the recycling or stabilisation of waste with limited external resupply [5,6]. Bioregenerative work on the MELiSSA loop, for example, demonstrates the operational complexity of coupling microbial, plant, and engineered subsystems to recover key resource streams under closure [12]. NASA's Life Support Baseline Values and Assumptions Document provides analysts and modellers with shared values and assumptions for comparing life-support studies and scenarios [22]. In this literature, sustainability is often measured by equivalent system mass, closure performance, reliability, consumables, waste handling, and crew-time requirements.

Human–system and habitability research extends this engineering logic by recognising that humans are not simply loads on a technical system. NASA-STD-3001 Volume 2 and the Human Integration Design Handbook place habitability, environmental health, human factors, and interface design at the centre of safety and performance [7,8]. Space-habitat design scholarship further demonstrates that isolated and confined environments require attention to privacy, spatial organisation, sensory quality, routines, interpersonal life, and the long-term usability of the built environment [27]. These concerns are conditions under which resource-constrained systems remain liveable and operationally effective.

Space analogues are particularly valuable because they make the interaction between resource constraints and human experience observable. HERA, NEEMO, and related analogues simulate isolation, confinement, remote operations, and mission-like routines [9,28]. Recent analogue reviews argue that such environments can support behavioural health, performance, and team research, but also warn that analogue studies often vary in methodology, duration, mission profile, and measurement quality [10]. This heterogeneity reinforces the need for a flexible framework that can compare conditions, practices, and outcomes without assuming all analogues are equivalent.

The relevance of analogue habitats is also illustrated by historical spaceflight experience, particularly the Shuttle/Mir programme. NASA-funded Shuttle/Mir studies reported that interpersonal issues in multicultural crews included tension, cohesion, leadership, lan-

guage and cultural factors, and displacement of negative emotions, and found differences between American and Russian participants and between crew and mission-control personnel [29,30]. Related Mir-simulator evidence similarly reported increasing tension, declining cohesion, changes in communication with external monitoring teams, and displacement of tension towards monitoring personnel, while Shuttle/Mir critical-incident logs generally concerned on-board events and interpersonal conflicts. These findings led researchers to discuss countermeasures in training, leadership support, crew–ground communication, and multicultural preparation [29,30]. Astronaut journal analysis from later ISS expeditions likewise shows that work, communications with mission control and family, adjustment, interactions with crewmates, recreation, equipment, sleep, and food are recurrent elements of long-duration mission experience [26]. Professional communities such as the Association of Space Explorers, which brings together flown astronauts and cosmonauts from multiple national programmes and promotes international cooperation, further illustrate that the astronaut perspective is inherently experiential, intercultural, and operational rather than solely technical [31]. These historical lessons clarify why analogue missions should not merely test hardware or resource closure. They can be used to trial routines for meals, hygiene, private time, social rituals, shared service labour, conflict-sensitive protocols, and crew–ground support before such routines are embedded in real missions. Closed-loop hospitality therefore provides a mechanism for translating past mission lessons into measurable analogue interventions: if hospitality protocols improve legitimacy, cohesion, compliance, and recovery while remaining within resource limits, they may help reduce the social and operational vulnerabilities observed in long-duration missions.

The term space analogue should also be specified more carefully, because different analogue settings simulate different mission risks. Short- and medium-duration confinement facilities are useful for studying routine compression, workload, privacy scheduling, and crew–ground procedures; undersea analogues emphasise safety-critical teamwork, small-volume living, and EVA-like operations; lunar-oriented simulations foreground surface operations, dust or contamination management, partial closure, and shorter-cycle logistics; Mars-oriented simulations foreground long duration, communication delay, autonomy, food monotony, delayed resupply, and limited external support; and Antarctic or polar winter-over stations add real environmental danger, prolonged darkness, evacuation constraints, and medical autonomy as psychologically prominent burdens [9–11,23,24,27,28]. The framework should therefore be applied as a mission-type-sensitive assessment architecture rather than as a single, uniform checklist. Table 1 indicates how the same closed-loop hospitality domains can be parameterised differently across analogue types.

Medical support is an important cross-cutting distinction among analogue types. In isolated habitats, access to diagnosis, treatment, evacuation, and psychological reassurance influences how confinement is experienced and how crews evaluate the legitimacy of restrictions. For short- and medium-duration laboratory analogues, emergency evacuation may be rapid, so medical care mainly serves screening, monitoring, and reassurance functions. In Antarctic and polar winter-over stations, evacuation may be delayed or practically impossible in real operational terms. In Mars-oriented analogues, the psychological burden of limited access to external care is usually simulated through restricted support, delayed communication, autonomy requirements, predefined withdrawal or termination rules, or other deliberately constrained mission procedures rather than through the same literal impossibility of evacuation. Such situations can increase psychological burden and require greater medical autonomy, in-crew health competence, telemedicine protocols, pharmaceutical and diagnostic stocks, and clearly communicated thresholds for withdrawal or termination. Medical support therefore affects both crew composition (e.g., inclusion of a physician or medically trained crew member) and the hospitality layer of habitation

because perceived care, safety, and access to help are basic conditions for dignity and compliance under isolation [7,23–25,28].

Table 1. Mission/analogue differentiation for applying the closed-loop hospitality framework.

Closed-Loop Hospitality Aspects to Emphasise	Distinctive Constraints	Analogue or Mission-like Setting
Privacy scheduling, workload balance, hygiene thresholds, routine legitimacy, crew–ground communication, and recovery after disruption [9,10]	Schedule density, limited privacy, crew-time scarcity, behavioural monitoring, and protocol adherence	Short-/medium-duration confinement facilities, e.g., HERA
Shared-space etiquette, care and attentiveness, service-role rotation, conflict prevention, and coordination rituals [28]	Small habitable volume, saturation or underwater operations, EVA-like tasks, safety dependency, and operational interdependence	Undersea operational analogues, e.g., NEEMO
Cleanliness standards, dust-control routines, airlock etiquette, provisioning design, maintenance labour, and comfort-versus-resource thresholds [5,11,27]	Shorter evacuation and resupply logic than Mars, dust/contamination control, EVA cadence, storage limits, and maintenance burden	Lunar-oriented simulations and surface testbeds
Food variety, communal rituals, private time, perceived care, fairness of domestic labour, legitimacy of restrictions, and resilience under disruption [10,11,24]	Long mission duration, food monotony, delayed support, limited medical capability, high autonomy, and cumulative psychosocial load	Mars-oriented long-duration simulations
Medical reassurance, social rituals, culturally acceptable routines, care labour, privacy, conflict prevention, and dignity-preserving minimum conditions [23,27]	Seasonal darkness, weather-imposed confinement, evacuation delay, limited medical support, multicultural crews, and high dependence on local routines	Antarctic/polar winter-over stations

Source: Authors.

3.3. Psychosocial Wellbeing, Team Dynamics, and Isolated Confined Environments

In isolated and confined environments, sustainability partly depends on whether occupants can maintain wellbeing, cohesion, identity, and compliance under constraint. Reviews of psychosocial issues in extreme environments identify isolation, confinement, monotony, loss of privacy, interpersonal tension, sleep disruption, and role stress as persistent risks [23]. Mars-500 findings similarly show that long-duration simulated missions can produce measurable behavioural and psychological changes over time [24]. Altman’s foundational analysis of privacy as a dialectical, regulated process of access to self and others provides a useful anchor for theorising how spatial and temporal protocols mediate dignity and wellbeing under confinement [32].

Research on team dynamics reinforces this point. Bell et al.’s systematic review of analogue research shows that long-distance space missions require attention to team composition, cohesion, conflict, performance, autonomy, workload, and shared adaptation [25]. Stuster’s analysis of astronaut journals adds a lived-practice perspective, showing that food, sleep, interpersonal issues, recreation, personal time, habitat design, and work routines are recurrent elements of long-duration mission experience [26]. These sources support the manuscript’s claim that daily routines are related to sustainability as mechanisms by which systems remain tolerable, legitimate, and recoverable. Validated short instruments such as the WHO-5 Well-Being Index [33] and the NASA-TLX workload scale [34] illustrate

the type of low-burden measures that can be embedded in analogue routines without overloading occupants.

As most activities in our studied domain are international, cross-cultural composition should be treated not only as a demographic descriptor but also as a design variable for analogue crews. Evidence from Shuttle/Mir and wider spaceflight psychosocial research indicates that language practices, national-organisational work styles, expectations of command, perceptions of autonomy, food norms, privacy boundaries, hygiene expectations, conflict expression, and crew-ground relations can become operationally relevant under confinement [25,29,30]. For closed-loop hospitality, such differences shape what is considered fair, dignified, clean, acceptable as food, appropriate as care, and legitimate as rule enforcement. Analogue missions should therefore document cultural and linguistic crew composition, previous intercultural preparation, role distribution, common-language competence, and culturally salient routine requirements as condition variables. This does not imply that cultural diversity is itself a problem. Rather, poorly designed routines can convert unacknowledged differences into friction, whereas explicit hospitality protocols can support shared expectations, inclusion, and resilience.

A key limitation is that psychosocial and human-factors studies usually measure wellbeing, workload, or team processes as human outcomes rather than as mediators of sustainability. The closed-loop hospitality framework takes a further step by asking how specific routines—meal variety, hygiene thresholds, privacy rules, sensory modulation, or care labour—alter both human outcomes and resource-system performance.

3.4. Resilience and Socio-Technical Systems

Resilience scholarship adds an essential dimension, as sustainable habitation cannot be reduced to static efficiency. A habitat may appear efficient in narrow input–output terms yet still fail if it cannot absorb shocks, adapt routines, maintain legitimacy, or recover from disruptions. Steinmann et al. show that resilience in socio-ecological and socio-technical systems is measured through diverse metrics, but variables, units, and functional forms must be justified [4]. González-Quintero and Avila-Foucat similarly show that operationalising resilience often privileges attributes such as adaptability, disturbance absorption, connectivity, and diversity, while struggling to integrate feedback across subsystems [35].

Resilience engineering contributes a complementary vocabulary of monitoring, anticipation, learning, and response under uncertainty [36]. In closed habitats, these capacities are distributed across equipment, protocols, spatial design, and social order. A water-recovery fault, acoustic overload, food monotony, or conflict over cleaning work can all become resilience problems because they affect the capacity to maintain core functions over time. Hospitality practices therefore become relevant to resilience when they support trust, shared expectations, recovery routines, and perceived legitimacy.

3.5. Hospitality as Care, Comfort, Dignity, and Coordination Under Constraint

Hospitality scholarship is necessary because it provides a vocabulary for analysing the micro-social mechanisms that make constrained environments liveable. A longstanding challenge in the field is that hospitality is often treated either as an industry context or as an applied management domain, rather than as a robust theoretical object. Roberts and Shea explicitly call for stronger hospitality theory, noting that the field has often borrowed theory from elsewhere instead of developing its own conceptual resources [13]. Foundational works such as “In Search of Hospitality” and “Hospitality: A Social Lens” broadened the concept of hospitality beyond commercial provision, encouraging scholars to consider it as a social and cultural phenomenon [14,15].

At its most useful conceptual level, hospitality refers not simply to customer service but to the organisation of reception, care, bodily comfort, social order, and relations between host, guest, and shared space. The *Routledge Handbook of Hospitality Studies* positions hospitality simultaneously as a human phenomenon and as an industrial or organisational activity [16]. Chirinos is especially valuable because she links hospitality to human dignity and argues that hospitality should not be reduced to technical service delivery [17]. This distinction is crucial in confined habitats. When washing opportunities, food variety, acoustic privacy, attentiveness, or ritualised social contact are restricted, what is at stake is not merely satisfaction but the maintenance of dignity, recognisable personhood, and functional coexistence under stress.

Sustainable hospitality studies also show that hospitality practices influence water use, energy demand, waste, guest behaviour, and organisational routines in terrestrial settings [37,38]. However, this paper does not simply apply hotel sustainability to space analogues. It uses hospitality theory more fundamentally, as a means to interpret care, dignity, cleanliness, privacy, and service labour under strict material constraints. In this sense, closed-loop hospitality extends from commercial hospitality in space to a governance framework for resource-constrained care and daily life.

3.6. Integrated Gap

The reviewed literature provides a strong foundation but reveals a central gap. Existing research can assess whether a closed habitat is technically functional, habitable, or psychologically tolerable, but lacks a framework for evaluating how everyday practices of care, comfort, cleanliness, privacy, social ritual, and service labour affect sustainable resource use and operational resilience. This absence is significant. In closed-loop habitats, decisions regarding hygiene routines, privacy thresholds, service-role allocation, food variety, and communal rituals can affect not only perceived quality of life but also water use, waste generation, labour distribution, system load, rule legitimacy, compliance, and resilience under disturbance. Table 2 summarises how closed-loop hospitality differs from related concepts that address aspects of this terrain but do not integrate them.

Table 2. Distinguishing closed-loop hospitality from adjacent concepts.

Adjacent Concept	Main Concern	Why It Is Not Enough	What Closed-Loop Hospitality Adds
Habitability	Physical and environmental suitability of habitat	Often focuses on design requirements, usability, comfort, and performance	Connects daily living practices to resource governance and sustainability outcomes
Human factors	Human–system performance, safety, and workload	Can underplay dignity, care, ritual, and relational life	Treats care, comfort, and social routines as sustainability variables
Psychosocial wellbeing	Mental health, cohesion, stress, and adaptation	Often measured separately from material flows	Links wellbeing to water, food, waste, space, crew time, and compliance
Circular life support	Resource recovery, closure, and waste minimisation	Can remain infrastructure-centred	Shows how everyday practices affect closure, legitimacy, and system load
Hospitality studies	Care, welcome, comfort, service, and dignity	Usually not designed for materially closed systems	Repositions hospitality as constrained resource allocation and governance

Source: Authors.

4. Closed-Loop Hospitality as a Sustainability Assessment Framework

In closed-loop habitats, hospitality practices mediate between material constraints and the lived conditions of habitation. They influence environmental loads, social viability, and operational continuity, rather than merely adding comfort or aesthetic value. For this framework, we define the following key terms:

- Closed-loop hospitality: The design and governance of everyday practices of care, comfort, cleanliness, privacy, provisioning, ritual, and service labour within materially constrained and partially closed habitation systems;
- Hospitality design choice: A protocol, spatial arrangement, routine, or allocation decision that shapes how inhabitants access care, comfort, dignity, privacy, food, hygiene, and social support;
- Constraint variable: A resource, operational, or environmental limit that defines the feasible range of habitation practices;
- Minimum viable hospitality: The lowest level of hospitality provision that preserves dignity, privacy, perceived care, social legitimacy, and routine stability while remaining within the habitat's resource, processing, safety, and crew-time constraints.

Regarding the system boundary and functional unit, the primary system boundary is the inhabited analogue habitat and its immediate resource-support systems, including water, food, energy, air revitalisation, waste processing, habitable volume, storage, and crew-time allocation. Where relevant, the wider boundary includes resupply logistics and upstream resource provision. The preferred functional unit is the person-day, allowing hospitality practices to be assessed in relation to water use, energy demand, waste burden, labour time, and wellbeing outcomes per occupant per day. This unit does not replace mission-specific measures, such as equivalent system mass or reliability, but provides a practical basis for comparing daily routines.

Illustrative formulas include: water intensity of a hospitality practice equals litres used by that practice divided by person-days; waste intensity equals mass or volume of waste generated divided by person-days; closure ratio for a resource stream equals recovered or reused quantity divided by total demand; hospitality labour burden equals minutes of service, cleaning, care, or coordination work divided by person-days; and recovery time equals the time required to restore baseline routine after disruption.

The proposed framework begins with a simple yet significant proposition: in closed-loop habitats, scarcity is experienced through design and governance. Limits on water, energy, food, processing capacity, space, maintenance capability, and time are not encountered as abstract system parameters. Instead, they are manifested in meal routines, hygiene standards, privacy arrangements, task rotations, spatial etiquette, and the quality of care in daily interactions. The framework therefore redefines hospitality as the layer through which a habitat transforms its resource envelope into a pattern of inhabitation.

This approach is important for sustainability assessment because most resource utilisation models focus on throughput, efficiency, and closure performance, while habitability and psychosocial studies address wellbeing, performance, or stress. The closed-loop hospitality framework connects these domains by treating everyday living arrangements as design variables that influence both material loads and human outcomes. Hospitality is neither an optional luxury nor a synonym for subjective satisfaction; it is a socio-technical and normative mechanism that determines how resources are allocated, conserved, circulated, and perceived under confinement.

The first component of the framework is a set of constraint variables that define the habitat's operating envelope. These variables do not determine outcomes by themselves, but they set the feasible range within which hospitality choices must be made. Key variables include resupply interval, closure ratio, processing bottlenecks, redundancy and safety

margins, volumetric capacity, crew-time scarcity, environmental stress load, and mission or occupancy profile. The resupply interval refers to the time between external support events. The closure ratio indicates how extensively material flows are recycled within the habitat. Processing bottlenecks are limits in water treatment, air revitalisation, waste handling, food preparation, or cleaning throughput. Redundancy refers to backup capacity when conditions deteriorate. Volumetric capacity is the amount of space available for privacy, storage, hygiene, work, and collective activity. Crew-time scarcity recognises that labour and attention are themselves limited resources.

Intercultural crew composition is included here as well because the same resource rule or hospitality protocol may be perceived differently depending on language, prior mission culture, food practices, privacy norms, gendered or role-based service expectations, and cultural assumptions about care, authority, and conflict. Health-support capacity and medical autonomy should also be treated as constraint variables. They include the actual or simulated time to external care, the presence or absence of a medically trained crew member, telemedicine access, diagnostic and pharmaceutical capacity, emergency decision rules, and the psychological reassurance generated by credible care pathways. These variables shape feasible hospitality choices because hygiene thresholds, workload allocation, privacy during illness, food acceptability, rest routines, and the willingness to remain in isolation may all be affected when occupants perceive medical care as insufficient or unclear.

The second component is a set of hospitality design choices that make a constrained habitat liveable. These include provisioning design, hygiene and cleanliness standards, privacy protocols, social and communal rituals, care and attentiveness practices, sensory modulation, and service-role allocation. The important theoretical step is to treat these elements as deliberate choices rather than background conditions. A habitat may standardise meals or allow limited personalisation, define cleanliness at a very austere or a moderately restorative level, or rotate service labour evenly or permit hidden concentrations of caregiving and domestic work. Each choice has implications for dignity, fairness, labour burden, and material demand. Privacy, in particular, is best understood not as a fixed allocation of space but, following Altman, as a dialectical and culturally mediated regulation of access [32]. Table 3 illustrates how five representative design choices generate resource, social, and operational effects in parallel.

Table 3. Illustrative hospitality design choices and their resource, social, and operational effects.

Hospitality Choice	Resource Effect	Social Effect	Operational Effect
More frequent hygiene access	Higher water and processing load	Higher dignity and comfort	Higher maintenance demand
Standardised meals	Lower storage and waste variability	Possible monotony and lower morale	Easier provisioning and scheduling
Rotating cleaning roles	More even labour distribution	Higher fairness and legitimacy	May improve compliance
Scheduled private time	Requires spatial and temporal allocation	Higher privacy satisfaction	May reduce conflict
Communal meal ritual	Uses crew time and food resources	May strengthen cohesion	May improve recovery after stress

Source: Authors. Synthesised from [7,8,13–17,22,23,25–27,32,34,36–38].

The design choices and effect categories in Table 3 are grounded in the extant studies reviewed above. Hygiene access is linked to life-support baselines, human–system standards, and sustainable-hospitality work on water, sanitation, maintenance, and environmental

health [7,8,22,37,38]. Meal standardisation and food variety draw on isolated-environment and astronaut-journal evidence showing that food, monotony, recreation, and routines affect morale and adaptation [23,26]. Service-role rotation is informed by team-dynamics, workload, and hospitality studies that connect task allocation, care/service labour, dignity, fairness, and organisational routines to wellbeing and compliance [13–17,25,34]. Scheduled private time is based on privacy theory and habitat/habitability research showing that privacy is both a spatial and social-regulatory need under confinement [23,27,32]. Communal meal rituals are included because psychosocial, team-dynamics, astronaut-journal, and resilience-engineering studies associate shared routines, cohesion, trust, and recoverability with adaptation in isolated settings [23,25,26,36].

The third component defines the sustainability dimensions by which hospitality choices should be evaluated. Environmental sustainability is measured by resource intensity, closure or recycling performance, waste burden, and environmental quality load. Social sustainability is reflected in perceived dignity, equity of access, legitimacy of routines, privacy satisfaction, cohesion, and psychosocial wellbeing. Operational sustainability encompasses system reliability, maintenance burden, crew time consumption, protocol adherence, and adaptive resilience. In this framework, sustainability concerns whether a habitat can maintain acceptable living conditions and functional continuity within constrained resource cycles.

The framework's causal logic is relational rather than linear. Constraint variables determine the range of feasible hospitality design choices; these choices influence environmental, social, and operational outcomes; and the resulting outcomes inform subsequent design and governance decisions. A relatively generous hygiene regime may enhance dignity and comfort but increase water demand and treatment system load. Conversely, a highly compressed routine may conserve resources in the short term but undermine morale, reduce the perceived legitimacy of rules, and lower compliance with other conservation practices. Sustainable habitation is therefore a matter of calibration rather than simple maximisation or minimisation. Figure 1 summarises this logic by showing how closed-loop constraint variables influence hospitality design choices, how these choices produce environmental, social, and operational outcomes, and how monitoring feedback informs subsequent governance, protocol design, and threshold setting.

Minimum viable hospitality is the threshold concept of the framework. It refers to the lowest level of hospitality provision that preserves dignity, privacy, perceived care, perceived safety, social legitimacy, and routine stability while remaining within resource, processing, safety, and crew time constraints. The concept is not a call for luxury in constrained habitats. It identifies the minimum level of care, privacy, cleanliness, food acceptability, social recognition, medical reassurance, and recoverable routine required to sustain compliance and resilience without exceeding closed-loop limits. Table 4 summarises five threshold domains and their corresponding minimum viable conditions.

Table 4. Threshold domains and minimum viable conditions for closed-loop hospitality.

Threshold Domain	Minimum Viable Condition
Dignity and care	Occupants retain basic cleanliness, privacy, respectful treatment, and culturally acceptable routines.
Health support and perceived safety	Occupants have accessible medical screening, monitoring, first response, telemedicine, and evacuation pathways appropriate to the analogue type, along with clear withdrawal and termination thresholds.
Resource envelope	Hospitality practices do not exceed water, energy, waste-processing, storage, or crew-time limits.

Table 4. Cont.

Threshold Domain	Minimum Viable Condition
Operational continuity	Routines remain understandable, legitimate, and recoverable after disruption.
Social viability	Service and care labour are not unfairly concentrated, and routines do not systematically undermine cohesion or wellbeing.

Source: Authors.

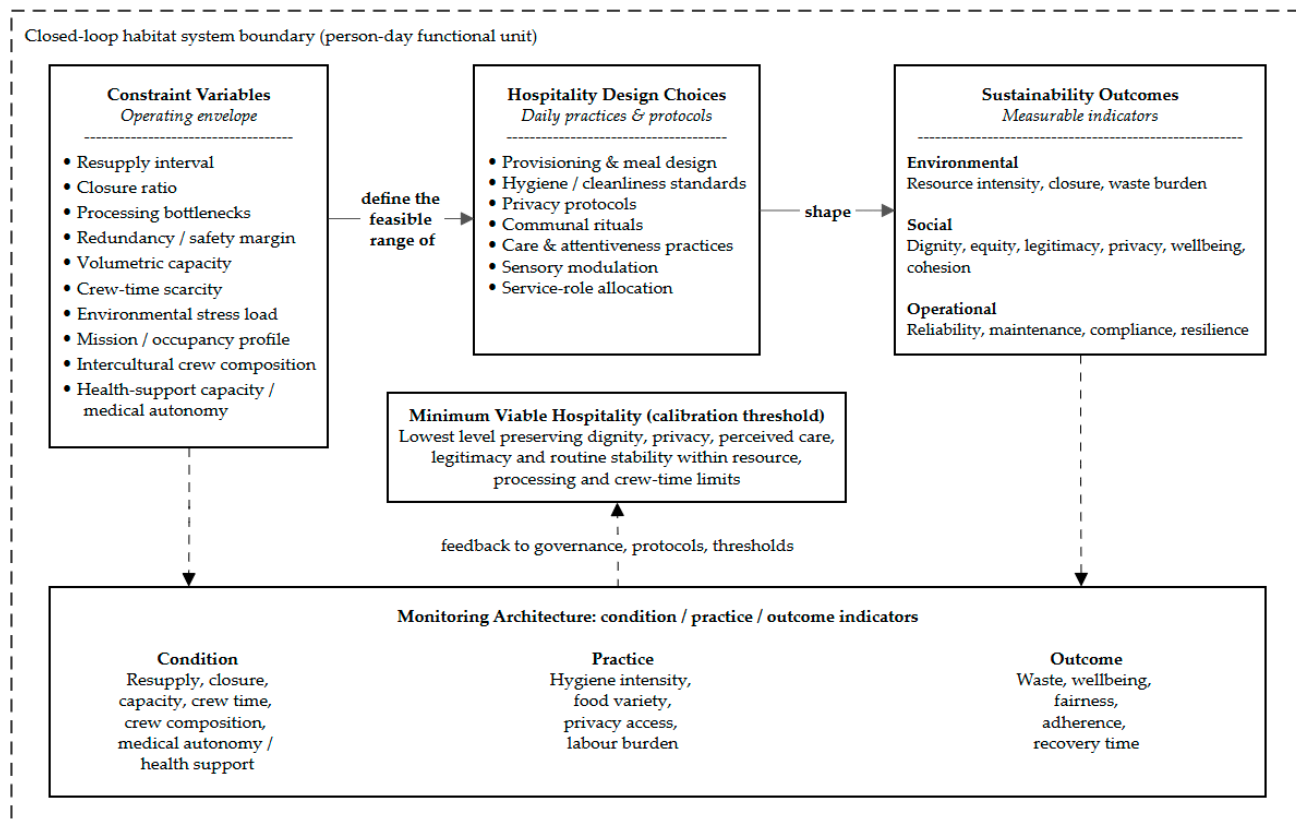


Figure 1. Closed-loop hospitality as a sustainability assessment framework. Constraint variables define the operating envelope of the habitat. Hospitality design choices translate these constraints into daily routines. These routines generate environmental, social, and operational outcomes, which can be monitored through indicators and fed back into governance, protocol design, and threshold setting. Dashed arrows indicate monitoring and feedback relationships between constraint and outcome indicators and the monitoring architecture. The feedback loops indicate that wellbeing, fairness, ritual, over-optimisation, and bottlenecks can support or undermine sustainable resource utilisation. Source: Authors.

5. Operationalisation: Monitoring Architecture and Propositions

The conceptual framework can be operationalised in two linked steps. First, it is translated into a monitoring architecture that identifies indicators for comparing hospitality-related sustainability performance across analogue settings. Second, these indicators are linked to a set of testable propositions connecting constraint variables, hospitality design choices, and measurable sustainability outcomes. Together, these steps transform the framework from an interpretive lens into an architecture for measurement, comparison, and decision support.

To strengthen the framework's connection to sustainability assessment, the conceptual model is translated into a measurement and monitoring layer. The aim is not to propose a validated empirical scale, but to identify indicators that would enable future studies to

define, compare, and monitor hospitality-related sustainability performance in closed-loop habitats. Indicators are conceived as selective but consequential devices: they determine what becomes visible, what can be compared across settings, and which trade-offs enter decision-making [2,3].

The monitoring layer operates at three levels. Condition indicators capture the habitat's baseline constraints, such as resupply interval, closure ratio, storage capacity, environmental stress load, available crew time, crew composition, and health-support capacity. Practice indicators capture how hospitality is configured through meals, hygiene thresholds, privacy scheduling, service-role allocation, and communal rituals. Outcome indicators capture the environmental, social, and operational consequences of those practices. This structure prevents sustainability claims from being reduced either to infrastructure metrics alone or to subjective satisfaction alone.

Table 5 proposes candidate measures. The Table should be read as an initial architecture for future testing, weighting, and contextual adaptation, not as a validated index. Threshold values will vary by habitat type, mission duration, crew composition, cultural expectations, and resource architecture. Several outcome measures draw on established short instruments that are feasible in analogue conditions, including the WHO-5 Well-Being Index [33] and the NASA Task Load Index [34].

Table 5. Proposed indicator matrix for closed-loop hospitality monitoring.

Level	Construct/ Indicator	Unit or Scale	Data Source and Frequency	Interpretation/Example Threshold Logic
Condition	Resupply interval	Days between support events	Mission plan; pre-mission and updated when support changes	Longer intervals increase pressure for closure and routine standardisation.
	Closure ratio by stream	Recovered or reused quantity/total demand (%)	Water, air, food, or waste process logs; daily/weekly	Lower ratios indicate higher dependence on stored or external resources.
	Processing bottleneck load	% of treatment, storage, or waste capacity used	Telemetry and process logs; daily	Sustained high load signals risk of hospitality compression or protocol revision.
	Habitable volume and privacy capacity	m ³ /person; number of private-use slots	Habitat plan and schedule; pre-mission/weekly	Low capacity increases privacy conflict and scheduling pressure.
	Crew composition and cultural preparedness	Crew national, linguistic, disciplinary, and role mix; prior intercultural training or briefing	Crew roster, training records, and pre-mission survey; pre-mission and when crew changes	Supports interpretation of food acceptability, privacy, care, labour fairness, conflict prevention, and legitimacy thresholds.
	Medical autonomy and health-support capacity	Evacuation delay; in-crew medical training; telemedicine access; diagnostic and pharmaceutical capacity; clarity of withdrawal/termination thresholds	Mission plan, medical protocol, crew roster, inventory, and pre-mission briefing; pre-mission and event-based	Higher autonomy requirements increase the need for in-crew competence, perceived safety, and medically realistic routine design.

Table 5. Cont.

Level	Construct/ Indicator	Unit or Scale	Data Source and Frequency	Interpretation/Example Threshold Logic
Practice	Hygiene water intensity	L/person-day for washing, cleaning, and sanitation	Water meters and task logs; daily	High values may improve dignity but increase treatment load.
	Food variety and food waste	Menu diversity index; kg/person-day or % prepared food wasted	Galley logs and waste audit; daily/weekly	Variety may support morale; waste indicates provisioning mismatch.
	Hospitality labour burden	Minutes/person-day for cleaning, provisioning, care, and coordination	Time-use diary and schedules; daily/weekly	Uneven burdens signal hidden operational and equity costs.
	Privacy access	Minutes/person-day of protected private time; rating 1–7	Schedule logs and pulse survey; weekly	Low access can erode dignity, stress recovery, and conflict prevention.
	Ritual and communal routine stability	Number and regularity of shared meals or rituals	Routine logs; weekly and post-disruption	Stable rituals may support cohesion and recovery.
Outcome— environmental	Waste burden	kg or L/person-day; separated by stream	Waste audit; daily/weekly	Rising burden may exceed storage, processing, or hygiene limits.
	Resource intensity of hospitality bundle	Water, energy, and consumables per person-day	Meters, inventory, and telemetry; daily/weekly	Supports comparison of alternative routine configurations.
Outcome— social	Subjective wellbeing	WHO-5 or adapted short wellbeing scale	Pulse survey; weekly	Decline suggests hospitality compression, stress, or workload imbalance.
	Workload and labour strain	NASA-TLX or adapted workload rating	Survey after key tasks or weekly	High workload indicates crew-time scarcity or unfair service allocation.
	Legitimacy and fairness	Acceptability and fairness ratings 1–7; conflict records	Pulse survey, debrief, and incident log; weekly/event-based	Low legitimacy may mediate lower compliance.
Outcome— operational	Protocol adherence	% checklist completion or observed adherence	Operational checklists; daily	Low adherence may reflect over-optimisation or low legitimacy.
	Reliability and maintenance burden	Uptime %, maintenance hours, and interruption frequency	Maintenance logs; daily/weekly	High burden may reveal hidden cost of hospitality routines.
Integrated	Minimum viable hospitality profile	Dashboard across dignity, medical reassurance, and resource demand	Composite scorecard; weekly and post-event	Balanced threshold: basic dignity, medical reassurance, and routine stability without exceeding resource limits.

Source: Authors. WHO-5 [33] and NASA-TLX [34] are referenced as established short instruments suitable for analogue settings.

Building on the monitoring architecture, the framework can also be presented as a set of propositions for future analogue research. These propositions specify expected

relationships between constraint intensity, hospitality design choices, and sustainability outcomes. They are intended to guide empirical testing, comparison across analogue habitats, and the design of quasi-experimental studies.

P1. Constraint intensity and hospitality compression. The greater the intensity of closed-loop constraints—especially longer resupply intervals, lower closure flexibility, tighter processing bottlenecks, and higher crew-time scarcity—the more hospitality design choices will shift towards compressed, standardised, and lower-variability routines. This can be tested through changes in provisioning variety, hygiene flexibility, privacy scheduling, and service role standardisation.

P2. Hospitality intensity and resource demand. More resource-intensive hospitality design choices, such as higher cleanliness thresholds, greater food variety, and more individualised provisioning, will be associated with higher environmental loads. This can be tested through water use, energy use, food loss, waste volume, and sanitation load per person-day.

P3. Dignity-supporting hospitality and psychosocial wellbeing. Hospitality design choices that support dignity, privacy, and perceived care will be associated with higher psychosocial wellbeing and stronger social cohesion. This can be tested using repeated wellbeing measures, privacy satisfaction, sense of belonging, trust, and conflict frequency.

P4. Legitimacy as a mediator of compliance. The more legitimate and fair hospitality routines are perceived to be, the greater occupant compliance with resource-conserving and operationally necessary practices will be. This can be tested with fairness ratings and protocol adherence logs.

P5. Communal rituals and adaptive resilience. Regular communal rituals and socially meaningful routines are associated with greater adaptive resilience, particularly by strengthening cohesion and improving recovery from disruptions. This can be assessed through post-disruption recovery time, trust measures, and routine-restoration logs.

P6. Service-role concentration and hidden operational burden. The more hospitality labour is concentrated in a small number of occupants or roles, the greater the maintenance burden, time scarcity, and risk of uneven wellbeing outcomes. This can be assessed using time-use diaries, NASA-TLX ratings, and role-rotation records.

P7. Over-optimisation and sustainability failure. When hospitality is optimised too narrowly for resource efficiency at the expense of dignity, privacy, and psychosocial support, overall sustainability performance declines due to reduced legitimacy, lower compliance, and weaker resilience. This can be assessed by comparing highly restrictive routines with those that balance resource conservation against minimum acceptable thresholds for comfort, wellbeing, and operational effectiveness.

P8. Minimum viable hospitality and integrated sustainability. Habitats that achieve a minimum viable hospitality profile—meeting threshold levels of dignity, privacy, care, perceived safety, medical reassurance, and routine stability without excessive resource demand—outperform both high-consumption and austerity-oriented configurations on integrated sustainability performance. This can be assessed through multi-criteria dashboards in analogue missions.

Future research should combine comparative case designs, quasi-experiments, and longitudinal monitoring. Analogue studies could manipulate meal variety, privacy scheduling, hygiene thresholds, or role rotation while measuring person-day resource demand, WHO-5 wellbeing, NASA-TLX workload, perceived legitimacy, protocol adherence, and recovery after disruption. Such studies would help determine whether closed-loop hospitality can function as a practical dashboard for habitat governance rather than merely as an interpretive concept.

6. Discussion

This paper makes three contributions to sustainability scholarship. First, it extends sustainability assessment into a domain that has largely remained conceptually dispersed: the organisation of daily life in materially constrained habitats. Sala et al. [1], Waas et al. [2], and Ramos [3] establish sustainability assessment as a multi-dimensional, decision-support practice, and Ness et al.'s taxonomy of tools [18] further clarifies the methodological choices involved. However, none of these contributions has been applied systematically to the lived practices through which inhabitants of closed environments consume, share, conserve, and contest resources. By framing hospitality as a measurable, sustainability-relevant layer of habitation, the present framework broadens the variables that can legitimately enter assessment scopes.

Second, the paper advances integrated sustainability thinking by linking environmental, social, and operational dimensions, rather than treating them as separate evaluative domains. This responds to Geissdoerfer et al.'s [19] argument that circular strategies do not automatically achieve sustainability, and to the diagnosis by Moraga et al. [20] and Saidani et al. [21] that circular economy indicators vary widely in what they capture and at what scale. By distinguishing condition, practice, and outcome indicators, the framework allows circular performance and social outcomes to be assessed jointly. In the proposed model, changes in dignity, legitimacy, or service-role allocation are mechanisms that may alter compliance, waste burden, labour use, and resilience.

Third, the paper supports quantification without oversimplifying the phenomenon it seeks to explain. This aligns with Steinmann et al.'s [4] argument that resilience and related socio-technical constructs require carefully specified variables and justified measures, while cautioning that their conceptual richness must not be lost in operationalisation. The framework therefore deliberately couples qualitative threshold concepts—dignity, legitimacy, and minimum viable hospitality—with operational measures such as water litres per person per day, percentage of checklist completion, and recovery time after disruption. The aim is not to reduce hospitality to a single score, but to make its sustainability consequences assessable across comparable units.

The framework is particularly aligned with research on resources and sustainable utilisation because it extends the meaning of resource use beyond technical throughput. In closed habitats, water, food, waste, space, and crew time are not only engineering variables tracked through life-support models [7,8,22] and bioregenerative system studies [5,6,12]; they are also governance variables that shape dignity, legitimacy, social order, and continuity. The framework therefore connects macro-level sustainability questions about closed-loop resource management with micro-level empirical questions about the daily practices through which sustainable utilisation is achieved or undermined.

For hospitality scholarship, the paper repositions hospitality in a non-commercial and high-constraint setting. It responds to Roberts and Shea's [13] explicit call for stronger hospitality theory and develops the social-lens approach proposed by Lashley and Morrison [14] and Lynch et al. [15]. It also aligns with Chirinos' argument [17] that hospitality should be rooted in human dignity rather than reduced to technical service delivery, while embedding that argument within material constraints rather than treating dignity as a purely normative concept. This makes hospitality measurable in closed-loop habitats, rather than considering it solely as a matter of symbolism or personal satisfaction.

A further contribution concerns how psychosocial findings inform sustainability analysis. Reviews of isolated and confined environments [23], long-duration simulation studies [24], analogue team dynamics research [25], and astronaut journals [26] consistently show that wellbeing, cohesion, workload, and conflict influence mission viability. The framework builds on these findings but takes an additional step: it treats psychosocial

outcomes both as ends in themselves and as mediators of resource-system performance. This aligns with resilience engineering's account of monitoring, anticipation, learning, and response as distributed capacities across technical, organisational, and social components [36], and with related operationalisations of socio-ecological resilience that emphasise feedback across subsystems [35].

Taken together, these contributions position closed-loop hospitality as an interdisciplinary bridge between mission experience, life-support engineering, human factors, behavioural health, medical support, intercultural crew studies, hospitality theory, and circular economy assessment. Its value lies in making daily routines such as food, hygiene, privacy, care, medical reassurance, role allocation, and waste handling visible as shared variables rather than separate technical, psychosocial, or service concerns. This interdisciplinary framing is intended to strengthen the relevance of analogue research for real missions while also clarifying its potential return for terrestrial circular-resource settings.

In practice, sustainable habitation in extreme environments should be seen as a calibration problem rather than a simple efficiency problem. Habitats that minimise resource use but erode dignity, fairness, or legitimacy may undermine the compliance and resilience on which long-term sustainability depends. Conversely, habitats that protect comfort without considering resource burdens may exceed the limits of closure and autonomy. Minimum viable hospitality offers a way to navigate this tension by identifying threshold conditions under which humane living and resource stewardship can be jointly sustained, rather than treating them as substitutes.

Although developed for space analogues, the framework may also inform remote research stations, submarines, disaster shelters, expeditionary healthcare facilities, polar camps, and circular hospitality operations on Earth, where resource constraints and well-being requirements intersect. Sustainable-hospitality scholarship has already shown that everyday practices in commercial settings shape water, energy, and waste flows [37,38]; the framework presented here generalises and refines that logic for materially closed contexts. The transfer is not mechanical: terrestrial circular hospitality is rarely as tightly closed as a habitat, and ethical, legal, and cultural settings differ. Nonetheless, the framework's emphasis on practices as governance variables offers a way to interpret terrestrial sustainable resource utilisation through a more granular lens, linking everyday routines to building-scale water, energy, and waste performance and to fair distribution of care and service labour.

The practical beneficiaries of the framework can therefore be specified more directly. Space agencies and analogue mission planners can use it to design protocols that make resource limits acceptable and legitimate rather than merely efficient. Habitat architects, life-support teams and operations managers can use the condition–practice–outcome structure to compare alternative routines, such as hygiene thresholds, meal systems, privacy scheduling, role rotation and waste-sorting protocols. Crew health, behavioural health and medical-support teams can use the framework to identify where resource-saving practices may create hidden risks for wellbeing, perceived safety or compliance. Hospitality and circular economy practitioners can use the person-day indicators to evaluate how water reuse, food-waste prevention, cleaning work, packaging reduction and care labour affect both environmental performance and user acceptance. Finally, funders and managers of remote terrestrial facilities can use analogue evidence to justify investments in circular systems that are socially durable rather than technically circular only.

The return value for the circular economy is therefore twofold. First, analogue missions can generate fine-grained evidence on how circular practices perform at the person-day level: litres of water reused, kilograms of food or packaging waste avoided, minutes of sorting or maintenance labour required, failures caused by bottlenecks, and changes in

wellbeing or compliance when routines become too restrictive. Second, they can inform terrestrial circular hospitality, remote infrastructure, high-performance buildings, and emergency or expeditionary facilities by showing how technical circularity interacts with dignity, fairness, hygiene, sensory comfort, and workload. This is relevant for funding and stakeholder engagement because well-designed analogue experiments that support future Moon or Mars habitation can also produce transferable knowledge for Earth-based circular resource governance, especially where water, waste, energy, space, labour, and wellbeing must be managed together [19–21,37,38].

The contributions outlined above should also be considered in view of several limitations. Most fundamentally, this is a conceptual paper. The framework has not yet been validated through empirical observation, comparative case analysis, or experimental manipulation. The proposed indicators and propositions should therefore be regarded as analytically grounded starting points rather than definitive measurement instruments or predictive laws.

A second limitation concerns construct validity. Closed-loop hospitality, minimum viable hospitality, dignity, and legitimacy require further refinement before they can be treated as validated constructs. Future work should test whether these constructs are empirically distinguishable from habitability, satisfaction, workload, or psychosocial wellbeing. A third limitation concerns analogue heterogeneity. HERA, NEEMO, Mars analogues, polar stations, and other isolated environments differ in duration, environmental stress, mission structure, autonomy, and crew composition. Any future application will need to adapt indicators and thresholds to the context.

A fourth limitation concerns cultural variability. Privacy, cleanliness, food acceptability, care, and dignity are culturally mediated. Thresholds that are viable in one crew or national context may not be viable in another. A fifth limitation concerns care labour and equity. Hospitality work may be gendered, role-based, or unevenly distributed, and future studies must make such burdens visible rather than treating them as background domestic labour. A sixth limitation concerns monitoring ethics. Wellbeing, compliance, privacy, and interpersonal data require careful consent, data minimisation, and governance. Excessive monitoring could undermine privacy and wellbeing, especially when sensors and pulse surveys are introduced in already constrained living quarters.

These limitations indicate several directions for future research. First, future studies should treat crew composition, language mix, intercultural preparation, and the distribution of hospitality labour as design and sampling variables rather than as background descriptors. Second, future research should record medical-support architecture, evacuation delay, in-crew medical competence, telemedicine access, and participant withdrawal protocols, as these factors may influence recruitment, crew composition, perceived safety, stress, and willingness to remain in isolation. Third, comparative studies across analogue habitats should examine how different hospitality configurations shape environmental, social, and operational outcomes under varying levels of closure and isolation. Fourth, targeted experiments should manipulate specific design choices such as meal variety, privacy routines, service-role rotation, and hygiene thresholds. Fifth, longitudinal studies should examine how hospitality practices evolve during fatigue, conflict, disruption, and adaptation. Sixth, methodological studies should pilot dashboards or multi-criteria scorecards to test whether the proposed monitoring layer improves decision support for habitat governance.

7. Conclusions

This paper argues that hospitality in closed-loop habitats should be regarded as a sustainability-relevant design and governance issue, rather than as an optional experiential layer. By developing the concept of closed-loop hospitality, the manuscript connects

material constraints, daily living practices, and measurable environmental, social, and operational outcomes within a single assessment framework. The central contribution is the identification of a neglected set of variables through which sustainable habitation under closure is either achieved or undermined.

The paper addresses its three research questions in concrete terms. In response to RQ1, the framework identifies the constraint variables that define a habitat's operating envelope: resupply interval, closure ratio, processing bottlenecks, redundancy, volumetric capacity, crew-time scarcity, environmental stress load, mission profile, intercultural crew composition, and health-support capacity and medical autonomy. In response to RQ2, it demonstrates how domains of hospitality design choice—provisioning, hygiene, privacy, communal ritual, care, sensory modulation, and service-role allocation—mediate between these constraints and corresponding environmental, social, and operational outcomes. In response to RQ3, it proposes a three-level monitoring architecture (condition, practice, and outcome indicators) and a candidate indicator matrix that enables hospitality-related sustainability performance to be defined, compared, and monitored across analogue settings.

For research on resources and sustainable utilisation, the framework offers a means to connect sustainable resource use with human dignity, psychosocial wellbeing, governance legitimacy, and operational continuity in extreme environments. It treats water, energy, food, space, and crew time both as engineering quantities and as governance variables enacted through routines. This dual perspective aligns with the integrated logic of SDG 6 (water), SDG 11 (sustainable communities), and SDG 12 (responsible consumption and production), as applied to the limiting case of closed-loop habitation, and extends to terrestrial settings—remote stations, expeditionary healthcare, polar camps, and circular hospitality operations—where everyday routines materially shape water, energy, and waste performance.

More concretely, when resource flows are instrumented, the framework positions analogue missions as circular economy laboratories in which water reuse, food-waste prevention, packaging reduction, repair and maintenance loops, waste sorting, and crew-time costs can be assessed alongside social acceptability and operational resilience. This strengthens the terrestrial relevance of analogue research because circular economy performance depends on infrastructure and on everyday practices that determine whether closed or semi-closed loops are actually maintained.

Several priorities emerge for future analogue research. First, candidate indicators should be piloted in HERA, NEEMO, polar, and Mars-analogue missions to test their feasibility and refine threshold values across contexts. Second, propositions P1–P8 should be examined through targeted experiments that vary specific hospitality design choices while holding constraint variables constant. Third, minimum viable hospitality should be tested as a calibration tool for habitat governance, rather than treated solely as an interpretive concept. In this sense, closed-loop hospitality is proposed as a practical analytical lens for assessing—and ultimately guiding—sustainable habitation under constraint.

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Abbreviations

The following abbreviations are used in this manuscript:

HERA	Human exploration research analogue
MELiSSA	Micro-ecological life support system alternative
NASA	National Aeronautics and Space Administration
NASA-TLX	NASA Task Load Index
NEEMO	NASA Extreme Environment Mission Operations
RQ	Research question
SDG	Sustainable development goal
WHO-5	World Health Organisation—Five Well-Being Index

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