Conceptual challenges in astrobiological analog environments and paths toward resolution

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This paper is a non-peer reviewed preprint submitted to EarthArXiv, currently not submitted to any journal.

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ABSTRACT:
Analog environments are terrestrial environments that resemble extraterrestrial sites; this concept originated in space sciences for defining methods to study planetary geology, training for missions and testing research instruments. As biological research became integrated into these investigations - through studies of limits for life and possible biosignatures - and astrobiology grew as a discipline, the term expanded in scope and nowadays analogy underlies much of the epistemic foundation of astrobiology. This expansion, however, also introduced conceptual inconsistencies: criteria for defining and evaluating analogs remain unclear, the term "analog" is increasingly misused, and analog environments are often treated as equivalent to extreme environments. Here we examine these conceptual issues and analyze them historically, highlighting the relevance of analogical-reasoning frameworks to resolve some of the indicated problems: it is possible to distinguish correct, incorrect, strong, weak and fruitful analogies and also apply principles such as transparency, adaptability and systematicity. We argue that a target must always be explicit; therefore, terrestrial organisms cannot be considered analogs for hypothetical extraterrestrial life, although they may serve as analogs for confirmed past terrestrial life. We clarify the differences between AAEs and extreme environments: AAEs require a defined target and occur only on Earth, while extreme environments are defined by obligatory extreme conditions and may occur anywhere in the Universe. Finally, we propose a refined and slightly broader definition of astrobiological analog environments (AAEs) as Earth-based environments that exhibit characteristics comparable to those of a target locale - whether another planetary body or Precambrian Earth conditions - whose selected features influence extant or fossilized biological components and allow researchers to develop an astrobiological understanding.

Keywords: astroecology, terrestrial analogs, planetary analogs, extreme environments, extremophiles, analogical reasoning, analogical mapping.

1. Introduction

An analog environment is a terrestrial environment that resembles an extraterrestrial one (Osinski et al., 2006; Léveillé, 2009). Those places present physical, chemical, geological and/or environmental characteristics that can be useful for studies encompassing astronomy, planetary science, astrobiology, astronautics, engineering and many other areas relevant to the space sciences. The vast panorama created recently by the dissemination of analog research has meant that the definition of analog itself depends on the interests of the scientists conducting the experiments. Foucher et al. (2021), in an attempt to solve this problem, developed a classification of "functional analogs", in which the analogy of the environments is defined by its use. They divided analogs into five categories but here we will focus on the so-called "*Analog sites of astrobiological interest*", or astrobiological analog environments (AAEs).

Astrobiology studies the origin, distribution and evolution of life in the Universe (Des Marais & Walter, 1999) and in that sense, AAEs are used for studying adaptations and evolutionary history of the lifeforms present there to understand limits of life and conjecturing about possible lifeforms that could be found elsewhere in the universe, exploring possible biosignatures, validating life-detection methods and other related topics, like testing ecological theories in unusual places (Meurer et al., 2024). Not so diffused in the astrobiological community is the idea that analog environments can encompass environments that resemble Earth's past conditions, as those are not included in original definitions of analog environments; however, they are very relevant for astrobiology because they provide clues about the origin and early evolution of life. For instance, submarine hydrothermal vents and terrestrial hot springs that serve as analogs for prebiotic environments (Deamer et al., 2019), and living stromatolites and biological soil crusts may enhance our understanding on Archean biota functioning and diversity (Burns et al., 2009; Thomazo et al., 2020).

The astrobiology literature on analog environments conceptualization is scarce, but this fact is not restricted to astrobiology only (Baker, 2014). Without analogy, the existence of astrobiology as a discipline would be severely threatened (Dick, 2014) and it has been suggested the vague or inadequate use of analogies can weaken the science of astrobiology (Nascimento-Dias et al., 2023). Thus, exploring ways to strengthen analogical reasoning in astrobiology is very important. The astrobiological community faces some issues on standardizing the criteria for interpreting analogs and even on conceptualizing what analogs are, as the misuse of the term "analog" is becoming more common in the literature. There is also a confusion between "analog environments" and "extreme environments" as those expressions are frequently presented as synonyms, which is another conceptual problem for astrobiology. Here we aim to discuss these topics, contextualize them historically and help resolve the pointed problems by reconceptualizing what is meant by AAEs.

2. The emergence of astrobiological analog environments and their definitions

It seems that the concept of "analog environment" arose spontaneously as a necessity for studying other planetary bodies and preparing for space missions. The interest in analog environments began at the end of the 19th century with predominantly geological assessments to improve current theories of planetary geology and later in the middle of the 20th century to train astronauts (Léveillé, 2010), while the firsts links between astrobiology and analog environments date back to the middle of the 20th century as well. At that time, a considerable part of the research was focused on understanding Mars' habitability - to test life detection equipment - and on survivability of microorganisms in harsh conditions for guaranteeing planetary protection, avoiding possible forward contamination by spacecraft.

The first NASA landers on Mars in the 1970's already conducted experiments for determining the presence of life on the surface of Mars (Biemann et al., 1976). Research on analogs from an astrobiological perspective was closely linked to the validation of life-detection methods at first but today its scope is much broader. Here we present (Table 1), a compilation of six review articles addressing astrobiology and analog environments, providing an overview of the state of the art in this field.

Table 1. Review articles on analog environments, with definitions used by the authors and the gaps and challenges they have identified, along with additional challenges we suggest here.

Reference	Definition	Identified gaps / challenges	Additional challenges
(Soare et al., 2006)	*"A terrestrial source mirroring conditions of a non-terrestrial target"*	➢ No clear rules or general criteria with which to evaluate the aptness or meaningfulness of an interplanetary analogy or terrestrial analog. ➢ New model proposed: there are only two orders of meaningful analogies. Analogies based on speculation (e.g: life on Europa because of life on Lake Vostok) would remain presumptuous.	➢ Referring exclusively to non-terrestrial target excludes analogs for Precambrian Earth, which are important for astrobiology as well as paleoecology.

(Léveillé, 2009)	*"Places on Earth that present one or more sets of geological or environmental conditions similar to those found on an extraterrestrial body, current or past."*	➢ Analog environments do not necessarily present all the conditions of an extraterrestrial setting.	➢ Referring exclusively to non-terrestrial target excludes analogs for Precambrian Earth, which are important for astrobiology as well as paleoecology.
(Preston & Dartnell, 2014)	*"Specific locations on Earth that are similar in some important respects to extraterrestrial locales"*	➢ No clearly defined and followed criteria with which to evaluate the analog sites. ➢ The accessibility of the environment sometimes can be more important than similarity with another planetary body. ➢ An open access repository for information about analogs is required.	➢ Referring exclusively to non-terrestrial target excludes analogs for Precambrian Earth, which are important for astrobiology as well as paleoecology.
(Martins et al., 2017)	*"terrestrial samples and field sites that resemble planetary bodies in our Solar System"*	➢ Analogs only mimic specific parameters of planetary bodies ➢ An ideal analog would mimic all properties, including compositional, electrochemical, physical and environmental aspects.	➢ No need for a "local" restriction in terms of our Solar System given the available data on exoplanets. ➢ Selection of AAEs reinforces a recurring unnecessary conflation between planetary analog environments and extreme environments in astrobiological framing.

(Foucher et al., 2021)	*"Functional analogues are defined as terrestrial sites, materials or objects exhibiting general properties more or less similar to those anticipated on the targeted extra-terrestrial body, but having specific analogue properties that are highly or perfectly relevant for a given use."*	➢ The term analog can be highly speculative when applied to (astro)biology. ➢ The perfect analog does not exist. ➢ Difficulties to choose the best-suited analog for a particular purpose (accessibility challenges).	➢ Implicit assumption that astrobiological relevance of analogue environments depends on the occurrence of extremophiles, overlooking broader adaptive or extremotolerant life strategies.
(Coleine & Delgado-Baquerizo, 2022)	*"natural Earth-based environments that resemble relevant extraterrestrial conditions"*	➢ Need for a framework of research and development that coordinates microbiome research within space life science. ➢ An open access repository for information about analogs is required. ➢ No analogue site is a perfect representation of another planet or moon.	➢ The term "natural" excludes environments that can be useful for astrobiology, like those impacted by human activity ➢ Selection of AAEs reinforces a recurring unnecessary conflation between planetary analog environments and extreme environments in astrobiological framing.

There are clear patterns that emerge from the reviewed definitions in Table 1. All authors emphasize that no analog site can fully replicate the conditions of another celestial body, and many highlight the lack of standardized criteria for evaluating analogs, along with logistical challenges in selecting or accessing suitable sites. Some describe analogs as environments that share “relevant” aspects with extraterrestrial settings, yet simultaneously criticize the absence of guidelines for determining which aspects should be considered relevant. Several articles associate analog sites with extreme environments, which can lead to conceptual confusion between these two types of environments (see Section 3).

Authors like Soare et al. (2006) and Foucher et al. (2021) note that studies on AAEs can become highly speculative, since life on other planets has not been found. The first argues that using Lake Vostok as an analogue for Europa’s potential biotic environment is speculative because our understanding of the prebiotic requirements for life’s origin is incomplete and there is a lack of direct data from Europa - so without sufficient target evidence, the analogy can not be meaningful. First, hypotheses like lithopanspermia suggest no need for the origin of life to occur on every inhabited astronomical body (astroecological dynamics like metabiospheres could be responsible for life occurring and persisting there; Mendonça, 2014). Second, and more to the point, while a critical viewpoint is essential when researching AAEs, it is important to recognize that all analogies, including the strong ones, contain a degree of speculation. Therefore, such analogs should not be dismissed, but rather approached and examined with greater caution and attention to detail.

Finally, due to the history of research on analog environments, the definitions typically excluded modern Earth-based environments that resemble Precambrian Earth environments. However, we suggest that a comprehensive definition for AAEs should incorporate such settings given the valuable astrobiological insights they offer. When referring to analogs of Precambrian Earth, we encourage authors to specify the relevant Eon (e.g., Hadean, Archean, or Proterozoic) or Era whenever possible. When precise temporal attribution is not feasible, broader terms such as “Precambrian” may be used. Even though an argument could be raised that this seems relevant for paleocology more than astrobiology, a “conceptual triangulation” can be conceived. Gains in understanding of the Precambrian Earth conditions through the study of contemporary Earth analogs can also be used to deepen our understanding of astrobiological situations, either in terms of the origin of life here and elsewhere or its evolution and occupation of different habitats.

2. Astrobiology and analogy

There are two main definitions for analogy that can be complementary for analog environments research. The first one comes from philosophy of science studies: *“Analogy is an objective property of pairs of systems”* (Bunge, 1981), and in that sense, it can help us understand analogical inferences and create better ones. The second one comes from psychology: *“An analogy is a mapping of knowledge from one domain (the base) into another (the target)”* (Gentner & Toupin, 1986), and it explains how people create and perceive analogies. The most clear use of analogy in astrobiology is in analog environments research, as they offer an ideal means to investigate inaccessible extraterrestrial settings (Nascimento-Dias et al., 2023). We should thus use a conscious application of theoretical frameworks for analogical reasoning on astrobiology.

2.1. Analogy as a property of two systems

In this section, we rely on the work of the philosopher of science Mario Bunge (1981, 1983), drawing directly from his text, below, to develop the necessary framework for understanding analogy in astrobiology. Analogical inference is a form of plausible reasoning because it relies on similarities between two systems to infer additional statements about other aspects of those same systems that may be analogous too. This is valid for astrobiological studies because every conclusion from analog environments studies about life on the universe will only be truly validated if we found life elsewhere in the universe or if Earth-based life thrives in extraterrestrial locales (e.g, future terraforming of Mars using Earthly microorganisms).

For Bunge, a system is defined by three components: composition, structure and environment. Composition is the set of recognised component units of the system, structure is the spatio-temporal position and relationship among system units, and environment is the context in which relationships occur, or the medium the units are in. Two systems can be analogous in each of those components, with different degrees of analogy (from 0 to 1), and the degree of total analogy is a mean of the degrees of similarities regarding each component of the two systems. Two systems are analogous if the degree of total analogy is greater than 0, weakly analogous if the degree of total analogy is close to 0, and strongly analogous if the degree of total analogy is close to 1. If the degree of analogy is significantly higher than 0 in at least one of the aspects, then the analogy is correct.

Note that the correctness of the analogy does not mean that the analogy is fruitful. Besides that, even in correct analogies, if the analogy is weak, the judgment that arises from it is superficial. Deep judgments proceed only from strong analogies. This form of evaluation, going beyond "right" or "wrong", is important for thinking about astrobiological analog environments. For example, stating that some analogies are weak and their judgement is superficial is different to concluding that the analogy is wrong. Since there are no "perfect" AAEs, and accessibility is an issue to research, we believe that it is plausible and acceptable to work with weak - but correct - analogies. Even if inferences are superficial, fruitful insights can be made. One approach that fits this perspective is *bioprospecting* for astrobiology, in which microorganisms are collected from their environment - that are not always "strong" AAEs - and subsequently tested under simulated extraterrestrial conditions to evaluate their resistance (Acevedo-Barrios et al, 2024).

Analogical inferences will never be closer to the truth than conclusions drawn from research *in situ*. "*Regard all analogies as heuristic devices. Be prepared to discard them if they cease to be useful.*" (Bunge, 1981). This rule can be a reminder for astrobiologists: we conduct analog research because we can not time travel or easily access other planetary locales. As a hypothetical example for this rule, if full research access to Mars is achieved, Earth environments analogous to Mars will become less relevant for astrobiological investigation, likely being restricted to mission planning.

2.2. Analogy and structure-mapping theory

Structure-mapping theory (Gentner, 1983) provides a model for how people understand and use analogies and perform other comparisons, like literal similarity. Analogies are created by three steps, which in a simplified way are: retrieval (choosing a target and a base), mapping (transferring knowledge and projecting inferences) and evaluation (judging the analogy and the inferences). In that sense, it moves beyond the mere enumeration of shared features, fundamentally defining analogy as a robust process of systematic knowledge transfer from a well-understood base domain to an unfamiliar target domain. When “analogies” share not only relational predicates but also object attributes, they are better described as literal similarities (Gentner and Markman, 1997).

Comparisons are not neutral processes: only specific commonalities between domains are highlighted during structure mapping, while others are deemphasized (Gentner and Markman, 1997). In analog research, scientists deliberately focus on the characteristics of the base domain that are meaningful for the target domain and for the research question. Differences between base and target can be categorized: alignable differences are directly linked to the shared relational structure, allowing for systematic contrast between corresponding elements of the two domains (e.g, soil *versus* regolith); non-alignable differences refer to features that are unique to one domain and lack a direct counterpart in the other.

In astrobiological studies, the presence of life on Earth is a non-alignable difference, as extraterrestrial life has yet to be detected. Life is a product of billions of years of evolution, that arose in specific conditions, and has been altering the planet ever since. So there is no other “object” in the target that could substitute life. This is a very strong non-alignable difference, and it helps explain the “strangeness” often associated with AAEs and why some researchers are still reluctant in this area. It is generally more tractable to interpret analogs related to the earliest stages of life on Earth since life now and life on the Precambrian are alignable differences.

There are many other factors taken into account when people perform analogical mapping and judge an analogy and its inferences. Those were explored by Gentner and Smith (2021) and we compiled some of them in Table 2 providing some astrobiological examples.

Table 2. Concepts derived from analogy theories, their definition as per the authors, and our suggested example in astrobiology.

Factor	Definition (Gentner and Smith 2021)	Example in astrobiology

Systematicity principle	People prefer analogies where many ideas are connected, not just one simple similarity. We value analogies that show how several relations fit together because they help us understand and create more inferences.	The analogy between ecosystems in Antarctic dry valleys and Mars' surface links several related factors, like extreme cold, dryness, limited nutrients, making it an informative comparison rather than a single similarity.
Transparency	How similar the compared things are. In a high-transparency analogy, the elements that have the same role are very similar (or the same), and the ones with different roles are clearly different.	Modern microbial mats and Precambrian microbial mats share similar structures and functions, making this a high-transparency analogy.
Adaptability	How easily an idea from one situation can be adjusted to fit another. People are more likely to accept analogies when the transferred idea can be easily adapted to the new context.	High-altitude desert ecosystems are better analogs for Mars than low-altitude deserts, because the second analogy would require more changes to make sense.
Goal relevance	We focus on analogies that are useful for the question or objective we are trying to address.	If the goal is to find life on Mars' surface, an analogy comparing Martian regolith to Earth's desert rocky soils is more relevant than one comparing Martian regolith to terrestrial ice caps, because the first is more helpful in guiding the search for life on the solid mineral surface.
New knowledge potential	Inferences that can provide new knowledge are desirable even if they are risky. This is important when we are facing unfamiliar domains.	We have not found life on other planets yet, but to understand how terrestrial life behaves and leaves detectable traces is an

important step for this outcome.

2.3 Applying analogical reasoning theories on astrobiology

Theories on analogy have been developed in fields outside planetary sciences, so their transposition to analog environments research should be done carefully. But by accepting they can contribute to astrobiology, some implications arise. The first one is that the definition of the concept of analog in astrobiology depends on the notion of a target (structure-mapping; Gentner, 1983) and on two well-defined systems (analogy as a property of pairs; Bunge, 1981). Without a target, the analogy loses its meaning, since any terrestrial environment could then be interpreted as comparable to a still unobserved extraterrestrial locale, and in that sense, all of the environments on Earth could be called analog environments. When using analogies in astrobiology, especially in the study of analog environments, it is important to define what is the target of the analogy (i.e, celestial body, environmental condition, etc). This notion is already present in Table 1, including two of the definitions using the term target/targeted (Foucher et al., 2021; Soare et al., 2006).

An issue emerges when one considers the search for life elsewhere. In practice, scientists are looking for life forms analogous to terrestrial organisms, since our only reference point is life on Earth, with its fundamental requirements such as liquid water and heat energy (De Mol, 2023). However, it is misleading to state that terrestrial organisms are analogs for possible extraterrestrial organisms, as those remain undiscovered and unknown in their characteristics and requirements. If such reasoning were accepted, then any terrestrial organism could arbitrarily be classified as an "analog". It is implausible to state that everything can be an analog, because the value of analogy in astrobiology lies in comparability - and we need pairs of systems to perform analogical reasoning. The less specific the target is, the more unconvincing the analogy becomes. For instance, the analogy between biocrusts and Archean Earth soils allows for a more detailed and complex analysis than the analogy between Earth's caves and "rocky worlds", since the latter is broader and less constrained.

3. Analog environments meet extreme environments: but are they the same thing?

Many articles on Table 1 suggested that the most relevant AAEs are the ones containing extreme characteristics and hosting extremophiles, and those with higher similarity will probably present more extreme conditions too. It is common to suppose that every AAE is an extreme environment. Recent literature tends to picture them almost as synonyms, and maybe this is why the idea of "analoguephile" was not conceived. But we need to be careful with the combination of broadness in the concept of "analog" (Session 2.1) with the vagueness in the concept of "extremes".

The study of microorganisms that could thrive in harsh environments started as a branch of microbiology. The term "extremophile" was coined by MacElroy (1974) when the research on extremophiles was relatively recent and few extremophiles were known. Discoveries of life in extreme environments started to gain importance to astrobiology (or at the time, exobiology) with the argument that if life could withstand hostile conditions on Earth, maybe it could withstand the same hostile conditions on other planetary bodies (Hoffman & Kontratos, 1969; DeVicenzi, 1984). Some of the extreme environments that were being explored in microbiological studies were also considered analog environments (Friedmann & Ocampo-Friedmann, 1984; Wharton et al., 1989). In the beginning of the 21th century, many articles delved into the connections between extremophiles and astrobiology (Hoover & Gilichinsky, 2001; Cavicchioli, 2002), a trend that we still see nowadays (Schultz et al., 2023; Noirungsee et al., 2024).

However, the concept of extreme environments and extremophiles has been a subject of discussion in literature. Friedman (1993) observed that although it is relatively easy to distinguish extreme from non-extreme conditions, objective criteria are not established; extreme environments are often presented as the ones that are inhospitable environments for humans. This anthropocentric view has been criticized for at least three decades, but we still lack better definitions. This debate remains far from consensus, raising an important question: how can AAEs be defined and evaluated in relation to extremophiles if they are grounded in a concept that also lacks objective and consistent definitions?

An outstanding advancement on this concern was proposed by Mariscal & Brunet (2020), that discussed the definitions of extremophiles from a philosophical perspective, listing five definitions of extremophily that are present - and conflicted - in the current research: human-centric, edge of morphospace, statistical rarity, objective limits and near impossibility. One possible direction for reducing bias in extremophile research is to emphasize empirical patterns, such as the observation that extreme environments typically exhibit reduced species diversity, often characterized by the dominance of specific taxa (Shu & Huang, 2022).

Addressing this question in depth is beyond the scope of the present study, although we believe that advancing this debate is important for astrobiology just like the debate on “what is life?” is (Cólon-Santos et al.., 2024). Rather than discussing definitions of extremophily, for now we suggest a clearer and more consistent application of the existing concepts. Table 3 presents differences and similarities between analog and extreme environments, offering a practical guide that may help reduce conceptual ambiguity in the identification and interpretation of AAEs.

Table 3. Differences and similarities in usage and applicability between astrobiological analog and extreme environments.

	Astrobiological analog environment	**Extreme environment**
Only exists when there is a target environment	Yes, otherwise it would be mere speculation.	No, not based on analogical reasoning.

(i.e, a planet or a past period of Earth)		
Initial discipline of study	Space sciences. Only studied when there are implications for space sciences.	Microbiology. Studies do not have to be related to space sciences.
Distribution	Only exist on Earth.	Can exist anywhere in the Universe.
Subjectiveness	It depends on the relationship between the base and the target proposed by the researchers.	It depends on the definitions of extremes and extremophiles used by researchers.
Extreme characteristics	Present in analogs with high transparency/fidelity.	Required.
Presence of extremophiles	Highly interesting for astrobiology and even expected, but not required.	Required if life is present. If only occupied by "mesophiles", then it is not extreme.

4. Evaluating analog environments

Fidelity is *"the degree of similarity of a particular analogue site to its counterpart on another planet"* (Osinski et al., 2006), a term that is similar to concepts of "transparency" (Gentner & Smith, 2021) and "degree of analogy" (Bunge, 1983). However, one of the main criticisms among analog environment researchers is that the criteria for evaluating analog environments are not well defined, since there are no tools to access this fidelity - just like there are no exact methodologies to access the total degree of an analogy (Bunge, 1983)

This problem is not prominent in AAEs for Precambrian Earth, where researchers can apply established paleoecological tools such as the Modern Analogue Technique and Analog Matching (Simpson, 2007; Schinteie & Brocks, 2017). Since research on other planetary bodies cannot rely on these Earth-centric biological records, new frameworks are required. Addressing this need, Stern et al. (2025) proposed the Narrative Approach and the Matrix Approach to assess ocean world analog environments. Before conducting fieldwork, researchers must define key processes, physicochemical parameters, methods, and logistical considerations to study the analog environment. Afterwards, specific criteria are tabulated to understand the strengths, challenges, or neutrality of the analog environment with respect to the scientific question. The authors defend that the chosen analog site is justified by its direct relevance to the research's purpose; this is linked with the "goal relevance" aspect in Table 2. This framework can enhance scientific rigor as it demands a well-developed science question and also can benefit research groups with less financial resources that can not access high-fidelity analog environments.

Types of analogs are divided into compositional (e.g., mineralogy, organic content), electrochemical (e.g., pH, water content), environmental (e.g., temperature, radiation) and physical (e.g, particle size and shape, albedo), and an ideal analog - one possessing 100% transparency - would mimic all those characteristics, although such an environment has never been recorded (Martins et al., 2017). Conducting research in weaker AAEs is not an insurmountable problem as long as the analogy is correct, but it is important that those issues are explicitly addressed in research development and description. The Matrix Approach (Stern et al., 2025) could also benefit from explicit associated similarity indices (e.g. average % CV between target and analog for fidelity processes and/or fidelity parameters, for example). The lower the percentage, and larger the similarity revealed, the more confidence in the validity of the analogy, but of course the number and importance of the quantified environmental factors is crucial as in any index. We urge all researchers to adopt this quantitative view as strictly as possible not only for defining projects, but also in reporting results, allowing much more objective assessments.

Finally, by decoupling the evaluation of AAEs from the mandatory presence of extreme conditions or extremophiles, we can enhance conceptual clarity. Since the validity of an analogy rests on the systematic mapping of relevant relations between the base and the target, an environment's "extremeness" should be viewed as a potential alignable attribute rather than a prerequisite for analogical fruitfulness. By prioritizing goal relevance and transparency, researchers can identify correct and fruitful analogies even if they are weak.

5. Conclusions and remaining challenges

We refine the definition of astrobiological analog environments as Earth-based environments that exhibit characteristics comparable to those of a target locale - whether another planetary body or Precambrian Earth conditions - whose selected features influence extant or fossilized biological components and allow researchers to develop an astrobiological understanding. We advocate that, in astrobiology, the word "analog" can only be used when there is a confirmed target. Consequently, terrestrial organisms must not be called analogs for extraterrestrial organisms until extraterrestrial life is discovered; they can, however, be called analogs for past confirmed life (e.g, modern stromatolites can be studied as analogs for precambrian stromatolites). We showed that extreme environments and AAEs may have a lot of aspects in common, but they can not be used as synonyms. AAEs are restricted to Earth and only exist when there is a defined target; while extreme environments can occur anywhere in the universe and are defined by obligatory extreme conditions and presence of extremophiles when life is detected. Finally, we demonstrated that recognizing interfaces between analog environment research and analogical reasoning studies can enhance AAEs proposals and evaluation: analogs that present high transparency and high adaptability, while adhering to the systematicity principle, are preferable and most likely to generate relevant new scientific knowledge. However, we acknowledge there are no "perfect" analog environments and accessibility is an issue to research, so we argue that it is plausible and acceptable to work with weak - but correct - analogies. If the scrutinies presented in this article are considered and discussed by the astrobiological community, then we could strengthen the science of astrobiology by democratizing AAEs research, decreasing semantic confusion and mitigating excessive speculation in future studies.

Acknowledgments

JCM would like to thank Andreas Kindel and Leandro Duarte for their suggestions on researching this theme; Igor Lima for the discussions about the concept of analog environments; and João Garcia for his considerations on the original draft.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process:

During the preparation of this work the authors used ChatGPT/OpenAI in order to improve readability and clarify sentences. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. All of the ideas in this paper were conceptualized by humans, and all of the references were retrieved by humans too.

References:

1. Acevedo-Barrios, R. et al. (2024) Bioprospecting of extremophilic perchlorate-reducing bacteria: report of promising Bacillus spp. isolated from sediments of the bay of Cartagena, Colombia. Biodegradation, 35, 601–620. doi.org/10.1007/s10532-024-10079-0
2. Baker, V. R. (2014). Terrestrial analogs, planetary geology, and the nature of geological reasoning. Planetary and Space Science, 95, 5–10. doi.org/10.1016/j.pss.2012.10.008
3. Biemann, K. et al. (1976). Search for organic and volatile inorganic compounds in two surface samples from the chryse planitia region of Mars. Science, 194(4260), 72–76. doi.org/10.1126/science.194.4260.72
4. Bunge, M. (1981). Analogy between systems. International Journal of General Systems, 7(4), 221-223. doi.org/10.1080/03081078108934823
5. Bunge, M. (1983). Epistemology & Methodology I: Exploring the World. D. Reidel Publishing Company.
6. Burns, B. P. et al (2009). Modern analogues and the early history of microbial life. Precambrian Research, 173(1–4), 10–18. doi.org/10.1016/j.precamres.2009.05.006

7. Cavicchioli, R. (2002). Extremophiles and the search for extraterrestrial life. Astrobiology, 2(3), 281–292. doi.org/10.1089/153110702762027862
8. Coleine, C. & Delgado-Baquerizo, M. (2022). Unearthing terrestrial extreme microbiomes for searching terrestrial-like life in the Solar System. Trends in Microbiology 30, 1101–1115. doi.org/10.1016/j.tim.2022.04.002
9. Colón-Santos, S. et al. (2024). Chapter 2: What Is Life?. Astrobiology, 24 (S1), S40–S56. doi.org/10.1089/ast.2021.0116
10. De Mol, M. L. (2023). Astrobiology in Space: A Comprehensive Look at the Solar System. Life, 13(3), 675. doi.org/10.3390/life13030675
11. Deamer, D., Damer, B. & Kompanichenko, V. (2019). Hydrothermal Chemistry and the Origin of Cellular Life. Astrobiology, 19(12), 1523–1537. doi.org/10.1089/ast.2018.1979
12. Des Marais, D. J. & Walter, M. R. (1999). Astrobiology: Exploring the origins, evolution, and distribution of life in the universe. Annual Review of Ecology and Systematics, 30, 397–420. doi.org/10.1146/annurev.ecolsys.30.1.397
13. DeVincenzi D. L. (1984). NASA's Exobiology Program. Origins of life, 14(1-4), 793–799. doi.org/10.1007/BF00933735
14. Dick, S. J. (2014). Analogy and the Societal Implications of Astrobiology. Astropolitics, 12(2–3), 210–230. doi.org/10.1080/14777622.2014.964132
15. Foucher, F. et al. (2021). Definition and use of functional analogues in planetary exploration. Planetary and Space Science, 197. doi.org/10.1016/j.pss.2021.105162
16. Friedmann, E. I. (1993). Extreme environments and exobiology. Giornale Botanico Italiano, 127(3), 369–376. doi.org/10.1080/11263509309431018
17. Friedmann, E. I. & Ocampo-Friedmann, R. The antarctic cryptoendolithic ecosystem: Relevance to exobiology. Origins Life Evol Biosphere 14, 771–776 (1984). doi.org/10.1007/BF00933732
18. Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. Cognitive science, 7(2), 155-170. doi.org/10.1016/S0364-0213(83)80009-3
19. Gentner, D. & Markman, A. B. (1997). Structure mapping in analogy and similarity. American Psychologist, 52(1), 45–56. doi.org/10.1037/0003-066X.52.1.45
20. Gentner, D. & Smith, L (2012). Analogical reasoning. In V. S. Ramachandran (Ed.), Encyclopedia of human behavior (2nd ed., pp. 130–136). Elsevier.
21. Gentner, D. & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. Cognitive Science, 10(3), 277–300. doi.org/10.1016/S0364-0213(86)80019-2
22. Hoffman, D. B. & Kontaratos, A. N. (1969). Biological generalizations and the search for extraterrestrial life (Report No. TR-69-710-1; NASA-CR-104060). Bellcomm, Inc.
23. Hoover, R. B. & Gilichinsky, D. (2001). Significance to Astrobiology of Micro-Organisms in Permafrost and Ice. In Permafrost Response on Economic Development, Environmental Security and Natural Resources (pp. 553–579). Springer Netherlands. doi.org/10.1007/978-94-010-0684-2_38

24. Léveillé, R. (2009). Validation of astrobiology technologies and instrument operations in terrestrial analogue environments. Comptes Rendus - Palevol, 8(7), 637–648. doi.org/10.1016/j.crpv.2009.03.005
25. Léveillé, R. (2010). A half-century of terrestrial analog studies: From craters on the Moon to searching for life on Mars. Planetary and Space Science, 58(4), 631–638. doi.org/10.1016/j.pss.2009.04.001
26. Macelroy, R. D. (1974). Some comments on the evolution of extremophiles. In BioSystems (Vol. 6, pp. 74–75). doi.org/10.1016/0303-2647(74)90026-4
27. Mariscal, C. & Brunet, T. D. P. (2020). What are extremophiles? A philosophical perspective. In C. Mariscal & K. C. Smith (Eds.), Social and conceptual issues in astrobiology (pp. 157–178). Oxford University Press.
28. Martins, Z. et al (2017, July 1). Earth as a Tool for Astrobiology—A European Perspective. Space Science Reviews. 209, 43–81. doi.org/10.1007/s11214-017-0369-1
29. Mendonça, M. S. (2014). Spatial ecology goes to space: Metabiospheres. Icarus, 233, 348–351. doi.org/10.1016/j.icarus.2014.01.027
30. Meurer, J. C., Haqq-Misra, J. & Mendonça, M. D. S. (2023). Astroecology: Bridging the gap between ecology and astrobiology. International Journal of Astrobiology, 23. doi.org/10.1017/S1473550423000265
31. Nascimento-Dias, B. L. et al (2023). As bases filosóficas da astrobiologia. Revista Opinião Filosófica, 14(1), 1–28. doi.org/10.36592/opiniaofilosofica.v14.1103
32. Noirungsee, N. et al (2024). Genome-scale metabolic modelling of extremophiles and its applications in astrobiological environments. Environmental Microbiology Reports, 16. doi.org/10.1111/1758-2229.13231
33. Osinski, G. R. et al (2006). Terrestrial analogues to Mars and the moon: Canada's role. Geoscience Canada, 33(4), 175–188. id.erudit.org/iderudit/geocan33_4art01
34. Preston, L. J. & Dartnell, L. R. (2014). Planetary habitability: Lessons learned from terrestrial analogues. International Journal of Astrobiology, 13(1), 81–98. doi.org/10.1017/S1473550413000396
35. Schinteie, R. & Brocks, J. J. (2017). Paleoecology of Neoproterozoic hypersaline environments: Biomarker evidence for haloarchaea, methanogens, and cyanobacteria. Geobiology, 15(5), 641–663. doi.org/10.1111/gbi.12245
36. Schultz, J. et al. (2023). Life on the Edge: Bioprospecting Extremophiles for Astrobiology. Journal of the Indian Institute of Science 103, 721–737. doi.org/10.1007/s41745-023-00382-9
37. Shu, W.S. & Huang, L.N. (2022). Microbial diversity in extreme environments. Nature Reviews Microbiology 20, 219–235. doi.org/10.1038/s41579-021-00648-y
38. Simpson, G. L. (2007). Analogue methods in palaeoecology: Using the analogue package. Journal of Statistical Software, 22(2), 1–29. doi.org/10.18637/jss.v022.i02
39. Soare, R., Pollard, W. & Green, D. (2001). Deductive model proposed for evaluating terrestrial analogues. Eos, 82, 501. doi.org/10.1029/01EO00299

40. Stern, J. C. et al. (2025). A comprehensive framework for assessing terrestrial analogue field sites for ocean worlds. Journal of Geophysical Research: Planets, 130, e2024JE008803. doi.org/10.1029/2024JE008803
41. Thomazo, C. et al. (2020). Biological Soil Crusts as Modern Analogs for the Archean Continental Biosphere: Insights from Carbon and Nitrogen Isotopes. Astrobiology, 20(7), 815–819. doi.org/10.1089/ast.2019.2144
42. Wharton, R. A. et al. (1989). Early martian environments: The Antarctic and other terrestrial analogs. Advances in Space Research, 9(6), 147–153. doi.org/10.1016/0273-1177(89)90221-4