How the "Habitable Zone" Frames Exoplanet Discovery Papers: A Quantitative Snapshot and an Epistemological Appraisal

Arthur Mary
PhD in Clinical Psychology, independant research

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Abstract

This article investigates the uses of the concept of the habitable zone (HZ) in recent exoplanetary research. A corpus of articles (n=24) published between 2022 and 2024 was constructed, and each text was analyzed with regard to its mobilization of the HZ concept. The results show that the HZ functions in two distinct ways: as a heuristic tool, guiding research by providing operational boundaries for habitability, and as a presumptive device, where its unexamined use tends to impose the idea that planets located outside the HZ are, by default, uninhabitable. These usages demonstrate how the concept not only structures the design of scientific inquiries but also frames the broader imagination of planetary habitability and the search for life.

Introduction

The "Habitable Zone" (HZ) as formalized by Kasting et al. (1993) and refined by Kopparapu et al. (2013, 2014) has become the *lingua franca* of exoplanet habitability. In discovery papers, the HZ frequently appears with a stabilized vocabulary ("conservative/optimistic," "Recent Venus/Early Mars," "Runaway/Maximum greenhouse"). Yet the same label is also used nominally (instrument names, rhetorical framing) without an operational definition. How often is "HZ" used as a concept with explicit bounds versus as a nominal tag? And how frequently do alternative frameworks (Hycean, H_2-greenhouse, desert, subsurface) appear alongside the Kopparapu HZ? Here I quantify the use of HZ language in refereed exoplanet discovery literature (2022-2024) indexed in ADS. I classify each article as Conceptual (C), Unqualified (U), or Instrumental (I), record whether Kopparapu is explicitly cited, whether "optimistic/conservative" bounds are used, and whether alternative frameworks or explicit critiques are offered. My goal is a snapshot of current practice rather than a verdict on which framework is "best." I defined Conceptual (C) as the use of the HZ with explicit bounds and sources (e.g., Kopparapu et al. 2013/2014; markers such as "Recent Venus/Early Mars," "Runaway/Maximum greenhouse"). Unqualified (U) denotes uses of "HZ/habitable/temperate" without bounds or sources. Instrumental (I) denotes non-operational uses (e.g., instrument names).

I do not address here the relevance of the Kasting–Kopparapu concept of the habitable zone. I will limit myself to recalling that it is based on the search for liquid water on the surface of rocky planets. This conception appears to have established itself as the canonical framework for the search for life elsewhere. However, other models exist. I will mention two: the H_2-greenhouse model (Pierrehumbert and Gaidos, 2011) and the desert-worlds model (Abe et al., 2011; Zsom et al., 2013).

Methodological approach

This study draws on the Astrophysics Data System (ADS) to survey refereed journal articles published between 2022 and 2024 containing the expressions "planet candidate" and "habitable" in their title or abstract. The objective is to capture a snapshot of contemporary scientific production related to exoplanet discovery. For each article (n=24), I assess how the concept of the habitable zone (HZ) is mobilized: whether its boundaries are explicitly defined, whether reference is made to a specific theoretical framework, whether alternative models of habitability are considered, whether the concept itself is discussed or refined, and whether the semantic field of life ("life," "living," "biotic," "biosignature,"

etc.) is invoked. The goal is not to evaluate the validity of the studies, but to examine the rhetorical and conceptual uses of the HZ in current research and publication practices.

I considered removing from the sample the mentions of "habitable zone" that originate from the name of the instrument: the Habitable Zone Planet Finder. Nevertheless, insofar as the instrument itself relies on an explicit definition of what it is searching for ("Our current understanding of biology and planetary physics suggests that in order to be habitable, a planet must be a rocky planet, like the inner planets of the Solar system," as stated on the website [consulted August 18, 2025]), it seemed appropriate to retain in the sample those articles that refer to it. It is, in any case, not insignificant that the concept penetrates into instrumental labels. Interestingly, one may consider that instrumentation, because it is never epistemologically neutral (Hacking, 1983), carries with it an operative definition that is not necessarily made explicit. This recalls Wittgenstein's proposal that the meaning of a concept lies less in the statement of its definition than in its handling and its use.

Table 1 presents the classification of discovery papers according to their use of the habitable zone. The table specifies whether the article refers to the Kopparapu HZ, whether the term is used conceptually, unqualified, or in relation to instrumentation. It also indicates whether alternative models are mentioned by the authors, whether the notion of habitability is debated, and finally whether the notion of life is addressed.

Data analysis

42% of the occurrences of the expression "habitable zone" in the corpus correspond to non-operational uses, that is to say, with no precision of what is meant by "habitable zone". The omnipresence of the expression in the abstracts (methodologically induced by my selection of articles) therefore does not imply a genuine conceptual mobilization. Over the 2022–2024 period, alternatives to the HZ–H_2O model are sparsely represented (21%), and only 13% in 2024. The pluralism of astrobiological conceptions that ought to guide the search for life thus remains timid to date.

The concept of the HZ (as defined by Kopparapu) appears to be less and less subject to discussion (criticism, nuance, etc.) over the years (27% of the articles in 2022, 20% in 2023, and 13% in 2024 provide elements of discussion about the concept). Of course, the size of our sample provides only an indicative trend, which must be interpreted with caution.

It is noteworthy that only four articles (16% of the corpus) explicitly mention the idea of "life" (in particular through expressions such as "*biosignatures*", "*optimal conditions for life*", "*activity of primitive life*", and "*search for life*"). These studies are all framed within the paradigm of the search for life on exoplanets. It is quite surprising that the notion of "life" is so scarcely present in our corpus. One might suspect that this is merely the result of a selection bias. Yet, if we rerun the query in the Astrophysics Data System (ADS) by substituting the criterion "*habitable*" with "*life*", "*biosignature*", or "*living*" (only referring to living beings), no articles outside of our original corpus emerge. My hypothesis is that the cautious notion of habitability has gradually taken root in the community and has, in practice, replaced that of life.

The discussions of habitability that appear in our corpus can be readily summarized as follows: emphasizing that candidate planets discovered within the habitable zone (HZ) may well not be habitable (Basant et al., 2022); showing that determining the HZ is more complex in binary-star systems (Sullivan and Kraus, 2022); and arguing that HZ boundaries alone are insufficient to establish habitability if atmospheric conditions are not considered (González-Álvarez et al., 2023a; Dholakia et al., 2024) . While one might judge these discussions to adopt only a modestly critical stance, it should be borne in mind that this is not the aim of these publications: they report exoplanet discoveries rather than address theoretical questions.

Article	Ref. HZ-Kop.	Cat. (U/C/I)	Alt. models	Hab. debate	Life
Peláez-Torres et al. (2024)	no	U	no	no	no
Jones et al. (2024)	no – but mentions "HZPF"	I	no	no	no
Dalal et al. (2024)	yes (optimistic)	C	no	no	no
Tschudi et al. (2024)	no	U	no	no	no
Dholakia et al. (2024)	yes	C	yes	yes	no
Eisner et al. (2024)	yes	C	yes	yes	no
Tran et al. (2024)	no – but mentions "HZPF"	U	no	no	no
Magliano et al. (2024)	yes (conservative)	C	no	no	yes : "optimal condition for life"
Matsuo et al. (2023)	yes	I	no	no	yes "biosignatures", "activity of primitive life"
Murgas et al. (2023)	yes (conservative)	C	no	no	no
González-Álvarez et al. (2023a)	yes (conservative)	C	yes	yes	no
González-Álvarez et al. (2023b)	yes (conservative)	C	yes	no	no
Lambert et al. (2023)	no – but mentions "HZPF"	U	no	no	no
Le Coroller et al. (2022)	no	U	no	no	no
Sulivan et al. (2022)	yes (conservative and optimistic)	C	no	yes	no
Kawauchi et al. (2022)	no	C	yes : hycean	no	yes "biosignatures"
Pinamonti et al. (2022)	yes	C	no	no	no
Basant et al. (2022)	yes	C	no	yes	yes : "search for life", "biosignature"
Kunimoto et al. (2022)	yes (conservative and optimistic)	C	no	no	no
Hurt et al. (2022)	yes (conservative)	C	no	no	no
Matsuo et al. (2022)	no	U	no	no	no
González-Álvarez et al.(2022)	no	U	no	no	no
Faria et al. (2022)	yes	U	no	no	no
Castro-González et al. (2022)	yes (conservative and optimistic)	C	yes : desert model	yes	no

Table 1: Conceptual, Unqualified, and Instrumental Uses of the Habitable Zone in Recent Literature

Thematic discussion

An expedient for researchers?

The concept of the habitable zone (HZ), even in its most "conservative" definition, retains a notable epistemological value: it is sufficiently flexible to open a space of possibilities in which discoveries can be framed as exciting. At a time when exoplanet detection has become routine, instrumental advances make it relatively common to report planets located within the region circumscribed by the limits of the HZ. In an academic context shaped by the ideology of *publish or perish*, the simple mention of a planet located "in the habitable zone (in the sense of Kopparapu)" ensures a form of scientific legitimacy, as well as the prospect of institutional recognition and funding (Bean et al., 2023).

By contrast, alternative or competing models that conceive of habitability beyond the sole potential presence of liquid water prove to be far more demanding: on the one hand technically and observationally, and on the other hand because of the greater argumentative burden they require to justify each case under study. For instance, Hycean worlds (Madhusudhan et al., 2021) or subglacial ocean worlds (Schwieterman et al., 2024) are regarded as compelling targets, but their validation demands complex atmospheric modeling, high signal-to-noise spectroscopy, and careful assessment of biosignature false positives. Such approaches require substantial observational resources and often entail a higher risk of inconclusive results (Tasker et al., 2020). In other words, exploring approaches alternative to the HZ (in the sense of Kopparapu) remains a riskier choice in terms of scientific productivity and academic career prospects. The current funding and mission-design landscape tends to prioritize Earth-analog, HZ-centric strategies—despite repeated community calls to broaden habitability research—thereby indirectly disincentivizing higher-risk programs that target non-H_2O-centric environments. (Cockell et al., 2020; Schwieterman et al., 2024).

An epistemic cost–benefit perspective

The epistemic gain from discovering life outside the classical habitable zone (HZ) would far exceed the gain from finding life under conditions closely resembling terrestrial ones. A second instance of life emerging under Earth-like circumstances would merely add another data point of the same kind. By contrast, uncovering traces of life based on a solvent other than water (or, better yet, organized according to principles not even envisaged by current speculative astrobiology) would dramatically expand our grasp of what life is, revealing that the form we know is likely just one special case within a broader and probably more diverse phenomenon. We must also reckon with the costs. Organizing the search primarily through the HZ lens (the Kopparapu paradigm) exposes us to a specific risk: the epistemic cost of a false negative (that is, overlooking a living world because it fails the HZ criteria) is much higher than the cost of a false positive (that is, the temporary excitement of a claim later refuted). It may even be that habitable, perhaps inhabited, planets have already been identified but received little attention precisely because they do not satisfy the filters that prioritize HZ-positive targets.

Reconsidering the research programs

What the Lakatos/Feyerabend dialogue makes clear is that there is genuine scientific value in the coexistence of competing models. Theoretical proliferation (HZ–H_2O, HZ–H_2, Hycean, subsurface, etc.) should be encouraged and, as far as possible, institutionally supported. A pragmatic way to foster such coexistence at the team level is to adopt minimal co-reporting protocols. In particular, discussions of exoplanet "habitability" for worlds in, near or out the Kopparapu HZ bounds should explicitly address the plausibility of alternative frameworks, even in a skeptical way, in light of the available data: planetary density, atmospheric conditions (especially the presence or retention of H_2), stellar irradiation relevant to desert-world inner edges, and 3D climatological contexts when they can be characterized, etc. A linguistic clause should also be adopted: the bare label "HZ" is insufficient. Without a qualifier ("HZ in the sense of Kopparapu"), it effectively renders invisible forms of habitability not predicated on surface liquid water. There is no doubt that the research program derived from Kopparapu's HZ concept has substantial heuristic value. However, if it suppresses the progressiveness of competing programs, it risks becoming degenerative in Lakatos's sense. Especially given that, in the absence of

any discovery of life to date, nothing allows us to assert with confidence that the Kopparapu-style HZ program is in fact progressive (though, obviously, it is still too early to say).

Epistemological obstacles

Following Bachelard (2002), one can identify several epistemological obstacles that impede the uptake of non-aqueous or non-surface-water models of habitability. First, the *obstacle of the sensible concrete*: because water is ubiquitous in terrestrial experience, it serves as a powerful psychological (not merely scientific) anchor that is hard to relativize. Second, the *obstacle of imaginary unity*: the seductive idea of a single "recipe" for life (liquid H_2O + carbon chemistry + CO_2 buffering) simplifies inquiry and coordination but biases assessment against alternatives, which appear fragmented, speculative, and resistant to unification. Third, the *instrumental obstacle*: our measurement regimes, spectroscopic databases, and climate models are optimized for H_2O–CO_2 systems, rendering alternatives less testable and thus less "scientific" under Popperian standards of falsifiability; what is readily measurable becomes reified as more real. Our dominant observing modes, widely used spectroscopic databases, and many climate models were historically built around Earth-like (N_2-H_2O-CO_2) atmospheres, which naturally privileges H_2O/CO_2 bands in detection and interpretation—even as new capabilities (e.g., ExoMol expansions; JWST studies of H_2-rich 'Hycean' candidates) begin to broaden that scope. Galison (1997) has shown that instrumentation carries with it implicit conceptual frameworks, which shape the definition and use of scientific categories. If we equip ourselves with tools specifically designed to make the HZ–H_2O hypothesis fruitful in terms of discoveries, then these tools will in turn reinforce a conception of habitability centered on this hypothesis.

Finally, the *linguistic obstacle*: in contemporary discourse "habitable" is tacitly equated with "liquid water at the surface," a semantic drift that tend to delegitimize scenarios involving ammonia, hydrocarbons, or ice-mediated and subsurface habitats by casting them as deviations from the default meaning rather than as competing, testable frameworks.

Rhetorical issues

When the expression "habitable zone" is used without any reference or definition, the Kopparapu definition is implicitly assumed. When articles employ the notion of the habitable zone without any technical specification of what is meant by it (no reference to authors or calculation methods), one may suspect that the use of this notion is primarily rhetorical. One can apply the following test: if replacing the expression "habitable zone" fundamentally changes nothing in the epistemic strength of the article, then it is not functioning as a concept but merely as a rhetorical device. In the articles that seem to use the notion in this way, "habitable zone" appears to serve as a synonym for the idea of "life." It is not impossible that we are witnessing a kind of rhetorical precaution: "habitable zone" would be a euphemistic turn of phrase to say that the discovered planet might harbor life. If rhetoric is the art of eliciting affects (Aristotle), then one must hypothesize that indicating that a planet lies in the habitable zone may have a performative aim (Austin). Just as it has been shown that, in scientific publications, the presence of brain images (even when irrelevant to the actual content of the article) tends to secure the assent of readers (including professional researchers) (McCabe and Castel, 2008; Mary, 2024), so too one may wonder whether the mere presence of the idea of habitability in an article similarly elicits favorable dispositions among readers (Latour and Woolgar, 1979; Fahnestock, 2003). Scholars of rhetoric of science such as Prelli (1989) have also underlined that scientific texts frequently rely on "epistemic rhetoric," in which terminologies themselves act as warrants of truth and legitimacy. In this sense, the recurrent, unqualified invocation of the "habitable zone" may be interpreted less as a precise scientific claim than as a rhetorical resource that enhances credibility and resonance within the scientific community.

The article by Matsuo et al. (2022) does indeed mention the notion of habitability, but only to illustrate that the instrumentation they propose will enable progress in the search for habitable planets; yet, strictly speaking, not only habitable planets. It would probably have sufficed simply to evoke the search for exoplanets. We can observe a subtle shift, notably in (Matsuo et al., 2022): the notion of the habitable zone "contaminates," in a sense, the object that occupies this space. By the mere fact of its presence within the HZ, a planet is described as a "habitable planet" or a "habitable planet candidate." by the mere fact of its position within a zone, even prior to any consideration of its atmospheric properties, in particular.

The expression "habitable," without any further qualification, as it is used in the scientific literature included in the corpus under study, seems implicitly and self-evidently to assume the Kopparapu-Kasting model. What this rhetorical use of the concept tacitly suggests is that a planet outside the habitable zone would, by definition (an implicit one), be considered uninhabitable. Strictly speaking, that is not scientifically accurate.

Conclusion

This survey of refereed exoplanet literature published between 2022 and 2024 reveals that the concept of the habitable zone (HZ) continues to occupy a central position in the rhetoric and framing of planetary discovery. Yet, in many instances, its use is non-operational: "habitable zone" appears without reference, definition, or discussion, functioning more as a rhetorical marker than as a scientific concept. The canonical Kasting–Kopparapu model, centered on the possibility of surface liquid water, implicitly dominates current practice, while alternative models of habitability remain marginal. This narrowing of conceptual space reflects both the institutional incentives of publish or perish and the non-neutrality of instrumentation designed with the HZ–H_2O hypothesis in mind.

On the basis of this analysis, several practical guidelines can be drawn for researchers and authors:

- Always state explicitly the definition of the habitable zone used. This includes citing the relevant framework and specifying whether the conservative, optimistic, or another variant of the HZ is employed.
- Document auxiliary data relevant to alternative models whenever possible. Even if these data are not accessible, noting these limitations, or providing reusable data tables with orbital and stellar parameters or density or atmospheric conditions, enhances the value of published work for other habitability frameworks (e.g., H_2-greenhouse, desert worlds).
- Avoid "habitable" as a standalone adjective. Expressions such as "habitable planet candidate" risk overstating what is meant. Instead, authors should qualify usage, e.g., "a planet located within the classical HZ as defined by Kopparapu." This increases clarity and prevents the rhetorical slippage by which "habitable zone" implicitly becomes "habitable planet."

In conclusion, clarifying definitions, documenting data for alternative models, and exercising caution in rhetorical usage would strengthen the epistemic robustness of the field. Such practices would encourage a more pluralistic and transparent discourse on planetary habitability, supporting the broader development of search for life as a scientific enterprise.

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Corpus of articles

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