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RESEARCH ARTICLE

Why do we need (another) universal tracers portal in Astrobiology?

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Abstract

Astrobiology is a scientific field that is very interdisciplinary and developing very fast, with many new discoveries generating a high level of attention in both the scientific community and the public. A central goal of astrobiology is to discover life beyond Earth which is, with our current instrumentation and knowledge, arguably within our reach. However, knowledge exchange crossing disciplinary boundaries is becoming increasingly challenging due to different usage of nomenclature and scientific controversies often limited to subdisciplines. There have been some efforts to compile organized databases of terms, concepts and other relevant material within some of the subfields contributing to astrobiology, for example through manually curated online portals designed to benefit students, teachers and practitioners of astrobiology-related research. However, the developments within the subfields and the potentially premature communication of research findings are too fast for objective research portals to remain reliable and up-to-date enough to enable well-informed scientific discussions. We suggest here a novel strategy for developing an online tracers portal as a self-maintaining and self-updating information platform, that would allow not only for a relatively unbiased selection of research results, but also provide fast access to latest scientific discoveries together with potential controversies, such that users of the tracers portal can form their own opinion on all available data rather than obtaining an already filtered and potentially biased selection of information.

Contents

Introduction

Astrobiology encompasses research in different scientific fields and uses a multiplicity of methods, concepts and terms across various domains. As many disciplines are involved in astrobiological research (including many fields from natural sciences such as astronomy, astrochemistry, planetary sciences, geology, biology, biochemistry, meteorology, engineering, but also disciplines from humanities and social sciences including for example philosophy, theology, communication sciences, sociology, and arts), it becomes increasingly challenging for individual scientists to read, understand and contribute to work across different domains.

One way to help students, scientists, scholars and other interested parties to navigate this complexity is to build an online interface that facilitates access to the most useful, relevant and up-to-date information in the field.

Astrobiology could be subdivided into specific communities and research approaches depending on their target when investigating the possibility of life and habitability in different environments:

(1) When targeting the Earth, researchers focus on the early evolution of our planet and on the conditions necessary for life, tracing its early evolution for example via biomolecules or (micro) fossils, and studying potential limits of life as we know it.
(2) Communities investigating the inner solar system, especially Mars and Venus, search for tracers of past or present habitability, and preservability of tracers of especially extinct life (or even extant life today).
(3) Investigating the outer solar system, notably the icy moons of Jupiter and Saturn that hold vast amounts of liquid water in subsurface oceans, focuses on examining from orbit traces of their interior conditions found in ejected plumes that emit material from the interior into space.
(4) Exoplanet researchers focus on measurable tracers of habitable conditions (e.g., water, atmosphere) or even tracers of life (e.g., atmospheric gases in redox disequilibrium) when observable, for both rocky bodies and ocean worlds.

Within the various subdisciplines, astrobiology draws on a broad range of resources, methods, and tools in research related to tracers of life and habitability: laboratory experiments and simulations, fieldwork (often in analog environments), computational modeling and simulations, observational astronomy, space missions, as well as theoretical, philosophical and artistic approaches.

Here we use the word "tracers" to represent a range of terms used within these domains to describe evidence for habitable environmental conditions or evidence for past or present life, such as biotracers, bioindicators, biomarkers, or biosignatures (see Malaterre *et al*., 2023, for an overview of "biosignature" in particular). Indeed, the search for life follows different strategies in the four subdomains highlighted above, from in-situ measurements on Earth to remote sensing of exoplanetary atmospheres via spectroscopy, and the nature of evidence for habitability and life is very different from subfield to subfield, justifying our use here of a broader umbrella term, "tracers." One can speak of tracers of habitability, tracers of life, the preservation of different tracers, of true and false negative and positive tracers, of environmental interference with and preservation of tracers, and so on.

Currently, tracers are handled in a decoupled way within the above four subfields, and the meanings of the various tracer-terms furthermore vary between different scientific disciplines. While within each subfield the definition of any particular tracer is generally well-agreed upon, the same tracer name may have an entirely different meaning in another subfield (Figure 1). A biosignature for example may reasonably be (re)defined as "*any phenomenon for which biological processes are a known possible explanation and whose potential abiotic causes have been reasonably explored and ruled out*" (Gillen *et al*., 2023). While in the outer solar system community, biosignatures often refer to complex carbon-based chemistry associated with liquid water and identifiable by current or future instruments onboard a spacecraft (Klenner *et al*., 2024), in the exoplanetary context, the term "biosignature" has typically been used to refer to gases that in combination with specific other gases may be difficult to explain abiotically

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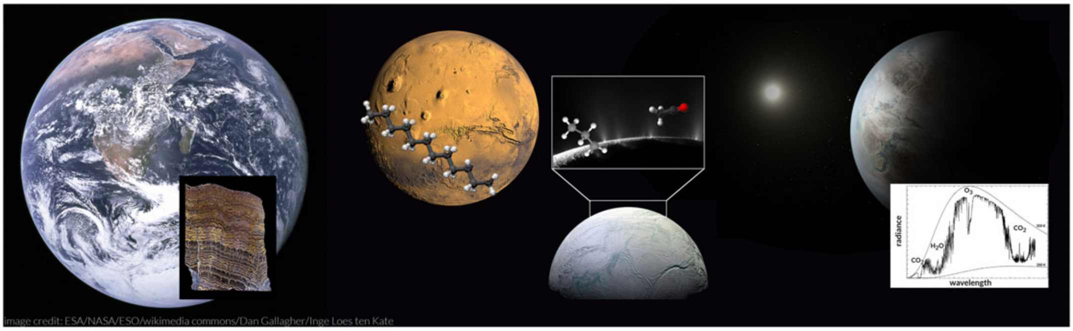

Figure 1. *Examples of tracers commonly cited but ambiguous because of possible abiotic origin shown here are a stromatolite showing the fossil record of Earth, organic matter as was already found on Mars, H_2 and CH_4 expelled from Enceladus' subsurface, and an example of an atmospheric spectrum of an Earth-like exoplanet. (Image Credit: ESA/NASA/ESO, Wikimedia Commons).*

(depending on their environment), although other traces may be possible to detect in the future (such as homochirality, Patty *et al*., 2021). One famous example for such a biosignature gas is oxygen, that has been handled for a long time as biosignature (in the form of more easily measurable ozone), but may for very specific cases be explained by abiotic processes (Luger and Barnes, 2015). Another example of varying nomenclature in different subfields are "ocean worlds," which in the (outer) solar system encompass different types of water bodies (most often referring to icy bodies with a subsurface water layer below an icy crust), whereas in the exoplanetary context ocean worlds are rocky bodies with surface water or (sub-)Neptunian bodies.

Thus, different subfields use different nomenclature, which can potentially lead to misunderstandings and miscommunications. In addition, confusion between tracers of habitability (which is the possibility to host life even if life was never present) and biosignatures create many challenges, specifically in communicating scientific discoveries (press articles have often misinterpreted studies of martian habitability as proof of life on Mars, for example).

For the unambiguous detection of life beyond Earth, or to trace the earliest life on Earth, we need to address three fundamental questions (Malaterre *et al*., 2023):

(i) Where do we need to search for life (tracers for habitability)?
(ii) What are we searching for (tracers for life)?
(iii) How do we correctly interpret our findings (preservation and environment of tracers)?

These questions, however, are strongly interlinked with each other, and a common portal addressing these various different types of tracers, developed in a way that minimizes disciplinary biases, is needed.

However, tracer or biosignature databases, that have been developed or suggested in the recent past (e.g. the *Life Detection Knowledge Base*, https://lifedetectionforum.com/ldkb), typically build on a specific nomenclature or encompass only a subfield of tracers studies (e.g. potential biosignature gases, Seager *et al*., 2016). Different types of tracers or biosignature portals have been developed in the past, though several efforts remain unpublished or are not openly accessible due to the huge task of providing a truly useful, stand-alone tracers portal and continuous maintenance and development work. Past initiatives include for example databases listing specific laboratory data (therefore linked to a small group of experiments/models/data), encyclopedia-like portals or wikis, where a small group of scientists provide potentially discipline-biased information, or websites of networks or societies linking to different projects, groups and research works (potentially regionally limited). All of these approaches have two main drawbacks – on the one hand they either require continuous maintenance and need

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continuous funding, or are at some point no longer up-to-date, once the funding of the project ends. On the other hand, if input is selected by a particular community/group of scientists, data will always be biased, for example, due to regional scientific developments or limited disciplines represented in the group.

Other scientific disciplines also are in need of general overview portals, and can guide the development of new portal developments in Astrobiology. One example are exoplanet databases, where, due to the discovery of many new planets each year (about 7500 known to date) and accompanying research efforts, continuous work is needed to maintain the latest knowledge developments. The strategy of the *NASA Exoplanet Archive* (https://exoplanetarchive.ipac.caltech.edu/) is to provide a complete overview of observational studies refining measurements of planetary properties such as planetary mass and radius, i.e., extracting the most useful information from individual publications. The European *Encyclopaedia of Exoplanetary Systems* (https://exoplanet.eu/home/) on the other hand provides the latest measured data but lists all publications related to the specific exoplanet, to give the user the broadest possible literature overview on the given exoplanet. While both strategies give the user the opportunity to trace the developments in observations, the maintenance work required is demanding, and the overview can at some point become too complex for well-studied exoplanets.

It should be noted that listing objects and their measured properties alongside reference publications is particularly well-suited for exoplanets, which can be compared in terms of similar sets of properties such as mass, radial velocity, orbital period etc., or focus on a specific system of interest (such as the TRAPPIST-1 JWST community initiative, Gillon *et al.*, 2020).

Such an approach however is inadequate for biosignatures for at least three reasons. First, biosignatures are extremely diverse and heterogeneous, meaning that their properties cannot always be compared (e.g., isotope anomalies in bio/geo-chemistry can be assessed in terms of microscopic structures whereas atmospheric gases in exoplanet research are investigated in terms of the spectral features). Second, given an object of enquiry – say, a rock or an exoplanet – different biosignatures are typically evaluated jointly (e.g., for exoplanet atmospheric gases: O_2 jointly with CH_4 when investigating redox disequilibrium, or with O_3 when investigating O_2-O_3 feedbacks), meaning that relationships between biosignatures are important to capture. Third, any biosignature will be investigated across a wide set of samples (e.g., isotopic anomalies across a diversity of rock samples). As a consequence, any biosignature portal needs to accommodate a diversity of data (capturing heterogeneous properties across biosignatures) alongside relationship networks (between biosignatures and their source objects, and between biosignatures themselves).

Proof-of-concept tracers portal

Building on a recently published review of biosignature concepts (Malaterre *et al.*, 2023), we aim to construct a user-friendly, universal, well-defined, open-access, online tracers portal, that would allow us to draw on new research inputs and concepts without the need of being maintained by a group of scientists (with a potential bias in selecting the portal input material).

In its current incarnation, see Figure 2, the portal retrieves useful literature related to core concepts in astrobiology/exobiology, including those relating to tracers of life and habitable environments. Important terms drawn from disparate but relevant fields can be selected with a click and combined with each other and with your own search terms. The portal is gathering publications via both the general Google Search Platform and Google Scholar and therefore remains more up-to-date and impartial than a human-curated database. In addition, by providing the potential of using broad categories of keywords in addition to freely defined search terms entered by the user, the portal can help guide the search for topics with much relevant research behind them. As an example, "biosignature"+"Mars" would lead to over 10,000 publications on scholar.google.com, but building on the current keyword structure of the portal, the search can quickly be limited to the more relevant subfields on Mars biosignature research that the user is interested in. In addition, the portal provides additional statistical information for the

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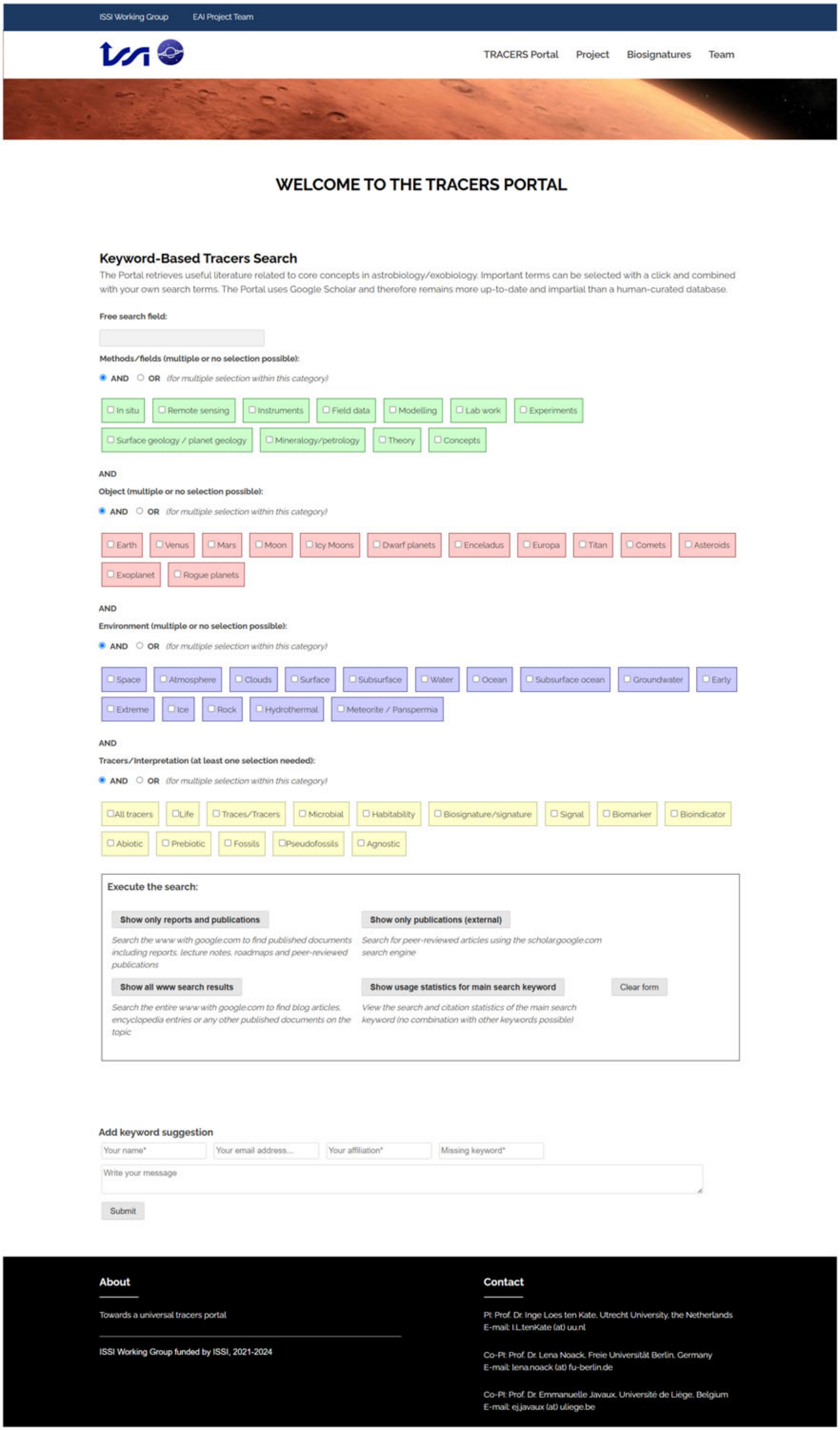

Figure 2. *Current proof-of-concept version of a self-maintaining portal (http://www.tracers-portal.eu), where the moderation effort is limited to updating keywords if needed, based on suggestions by the community.*

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main search keyword, which can be extended in a future development of the tracers portal to reach the full potential of the platform (see Discussion section).

We hope the portal will aid teaching and research by facilitating new connections, and will help newcomers to recognize and explore the diversity of terms and topics in astro/exobiology.

Our proof-of-concept portal offers different possibilities for gathering information on astrobiological research and tracer knowledge also by integrating a general search engine (here using google.com) to provide a current overview of the related online literature and media coverage. The search options currently include:

- Search the www with google.com to find published documents including reports, lecture notes, roadmaps and peer-reviewed publications.
- Search for peer-reviewed articles using the scholar.google.com search engine.
- Search the entire www with google.com to find blog articles, encyclopedia entries or any other published documents on the topic.
- View the search and citation statistics of the main search keyword (no combination with other keywords possible).

Supported by the International Space Science Institute (ISSI) and the European Astrobiology Institute (EAI), the TRACERS Team brings together a gender-balanced, multinational, multidisciplinary team of scientists and philosophers of science at different career stages. In addition, our concept of the portal was presented at two different Astrobiology conferences, specifically BEACON 2023 organized by the European Astrobiology Institute and EANA 2024 organized by the European Astrobiology Network Association.

On both occasions (see Figure 3), all conference participants were engaged in discussions on the setup of the portal and potential future developments, and were invited to shape the keyword collection of the portal by using post-its. The current portal is therefore already a larger community-driven effort reflecting many different disciplines and diverse backgrounds.

The usefulness of our proof-of-concept portal can be seen when searching for reporting trends in scientific literature in contrast to public online materials on controversial topics, such as "Phosphine," combined with keywords "Venus" and "Life," or "DMS," combined with keywords "Biosignature" and "Abiotic." For these recent examples (based on Greaves *et al.*, 2021, and Madhusudhan *et al.*, 2023, 2025), our portal directly shows the most recent research publications both in favor of the detections as well as publications pointing to different measurements or interpretations of the data, or abiotic production scenarios. Other portals (such as the Life Detection Knowledge Base) do either not (yet) deliver search results or provide more general, encyclopedia-style descriptions of the features that are selected, which are very useful for a general background information on the involved chemistry and physics, but do not contain up-to-date information on recent discoveries. Others (for example on Wikipedia) usually obtain fast updates from the scientific community, but typically with only a short update and linking to only one recent publication or news article, hence potentially not fully addressing the controversy.

These examples already show that our concept of a self-maintaining, living portal will provide more up-to-date information based on the most recent developments in the field. To exploit the full potential of our proof-of-concept portal, additional functionalities would be desirable, as described in the next section.

Discussion: The need for a new type of tracers portal

The above-described proof-of-concept portal is only the first step towards a new type of tracers portal, which should be mostly self-maintaining (i.e. with a structure that can also grow over time). The ideal portal would be a living portal staying up-to-date with new developments and findings in the community, and allowing full access to opposing views on critical discussions (see examples listed in

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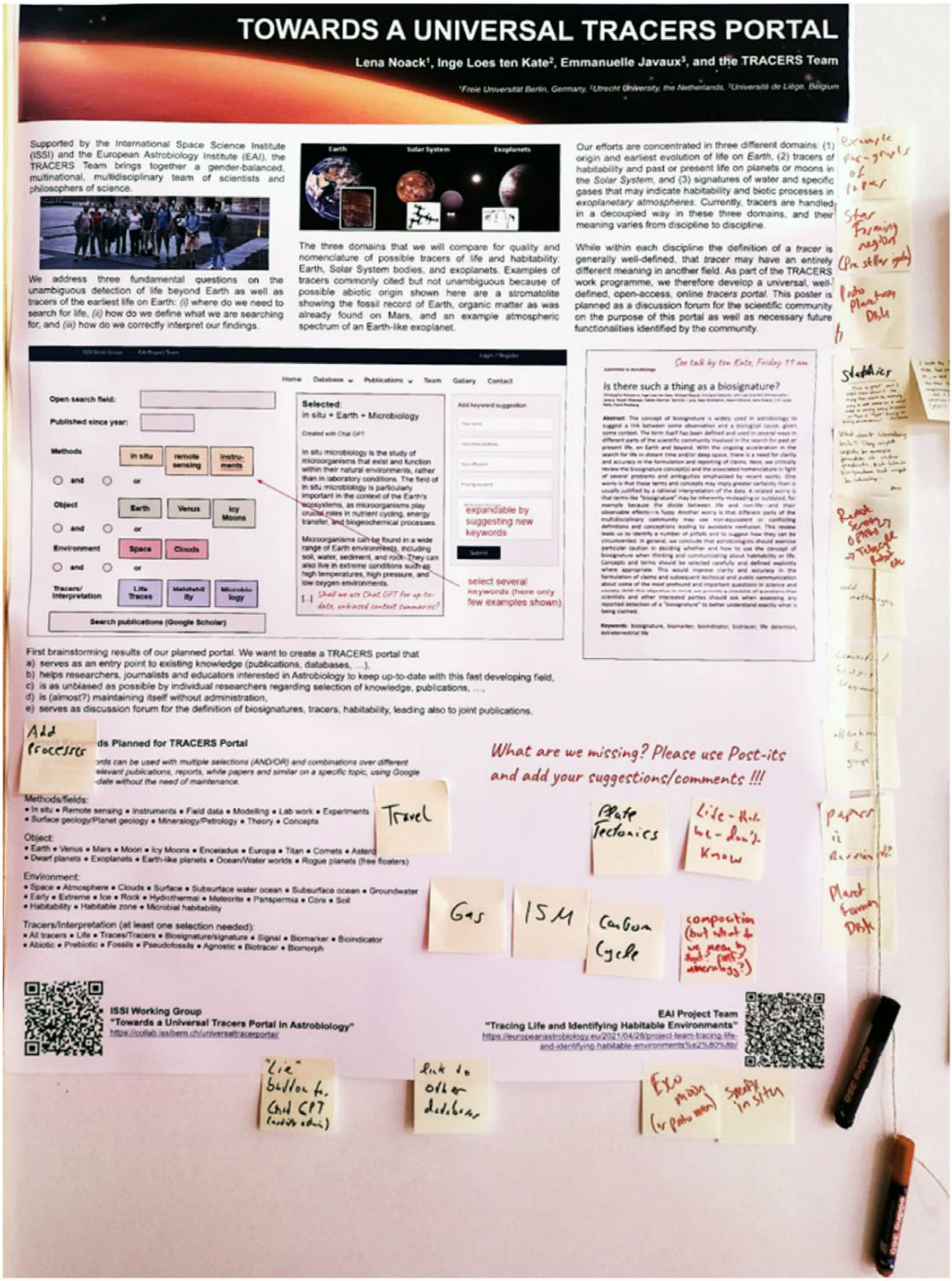

Figure 3. To create the first draft of the proof-of-concept portal, the idea of the portal and growing list of keywords were presented at different Astrobiology conferences, specifically BEACON 2023 and EANA 2024. This photograph shows anonymous feedback left by attendees at EANA 2024.

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previous section), including the opportunity to track the developments within a discussion (e.g. phosphine on Venus) to fully inform the user about opposing views and interpretation of data, or revision thereof, while remaining unbiased. An important basis of our idea of a new tracers portal is that information is not stored locally in the portal, but collected on the fly depending on the user's need, therefore continuously self-updating the provided data sets and knowledge.

The new generation of AI tools based on large language models also allows for new features to be explored within the framework of a new tracers portal, including for example on-the-fly generated encyclopedia-like summaries on the current state of knowledge for chosen combinations of keywords and/or search terms based on the current knowledge that AI tools are drawing on (hence with a potential lag time). It should of course be noted that large language models are not necessarily creating high-quality or trustable content, but these texts would likely be less biased than human-generated content. However, it will also likely not be able to develop a fully unbiased portal, as even with our proposed methodologies, the collected content may already be heavily biased by community-favored research topics. An exciting and new research topic (be it an especially interesting exoplanet, or a new potential biosignature detection) may dominate publicly available data (websites, blogs, news articles, and refereed articles) over less exciting, but more conservative articles.

Other potential and useful features of a new tracers portal could include the possibility to follow paths of synonyms to discover new connections between different keywords including tag clouds, especially for cross-disciplinary usages and research developments (similar to the PubMed database, https://pubmed.ncbi.nlm.nih.gov), and the possibility to sort search findings further based on suggested additional keywords, for example to divert into different research directions for controversial topics. Publication records could also be listed together with a citing paragraph surrounding the part of the article with highest score for the search keywords, which would especially aid the user in finding the appropriate knowledge to generate an own, informed opinion, especially for controversial topics.

A general tracers portal should of course also include statistical tools, for example with respect to usage of nomenclature in different subfields (such as Fig. 2 in Malaterre *et al*., 2023), citation statistics, and metrics on media coverage (as done already by a few scientific journals).

Beyond the automatic generation of user-dependent information, the portal could also serve as experts database based on either AI- or user-generated information, where the latter option includes the need for maintenance work and the drawback of potentially creating an uneven representation of subfields/disciplines or regions depending on how well known the portal would become in different subfields and parts of the world. The same potential exists for providing information on upcoming events in Astrobiology, by automated search potentially supported by user entries, though here also maintenance work would be generated to avoid imbalance and misuse of the portal.

The regional bias is also problematic with respect to the search algorithm, as keyword combinations linked to a specific nomenclature may lead to research output collected from a specific region of the world (e.g. French groups favoring "exobiology" over "astrobiology," Noack *et al*., 2015), which may also lead to one-sided data collection in cases where local working groups or networks influence regional research directions. A possible solution would be adding the functionality to limit (or exclude) search results to a specific region of the world by gathering more information from the publishers' websites such as affiliation of authors or e-mail addresses of corresponding authors, where in most cases the top-level domain (.uk/.cn/.edu/ . . .) can already be used for a rough, first-order regional mapping.

The above-described AI-generated features would, even when considering all potential drawbacks of AI, allow for a new platform serving the scientific community, educational institutions, as well as the informed public, while being independent of a specific research group, discipline, or subfield. Funding would also mostly only be needed for the initial development of the portal with its full functionality outlined above, with long-term costs limited to providing a permanent web presence and no or only negligible maintenance work. Our automated self-maintenance approach would therefore guarantee long-term usage potential of the portal, independent of project funding (or termination thereof), which is different to other Astrobiology portals currently developed in the community, that may need to cease to exist at some point when no further funding would be available.

Conclusion

In this article we highlight the need for a new type of tracers portal, in addition to existing community efforts in the broad field of Astrobiology. The design of the portal is based on the idea to create a self-maintaining, automatically self-updating and unbiased (as much as possible) portal that would not need substantial continuous funding or maintenance, and would therefore be independent of future funding or political decisions, and could serve as a long-term search portal in Astrobiology for researchers, educational purposes, and the interested public. The suggested tracers portal would also be an important tool for journalists to quickly inform themselves about different potential interpretations of new biosignatures or tracers pointed out in a publication or press release.

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Competing interests. The authors declare no conflicts of interest regarding this manuscript.

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