AL-MARSHAD: JURNAL ASTRONOMI ISLAM DAN ILMU-ILMU BERKAITAN
ISSN 2442-5729 (print) || ISSN 2598-2559 (online)
http://jurnal.umsu.ac.id/index.php/almarshad
DOI: https://doi.org/10.30596/jam.v11i2.28279 || Vol. 11, No. 2 Desember 2025

Bioastronomy and Life Exploration in the Universe: Conceptual Review and Educational Implications

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Abstract

Bioastronomy (astrobiology) explores the origin, evolution, distribution, and future of life in the universe and the search for life in extraterrestrial environments. This paper provides a conceptual review of key bioastronomy concepts—including biosignature definitions, habitability models, and both in situ and remote detection approaches—as well as examining pedagogical implications for formal and non-formal science teaching. The method is a systematic literature review of primary publications and reviews, along with a simple simulation to illustrate the application of a habitability index to a sample of hypothetical exoplanets. Findings show significant advances in biosignature assessment frameworks, life detection mission resources and strategies, and the growth of effective astrobiology education initiatives to enhance students' interest and critical thinking skills. Simulation demonstrates strong variation in habitability indices influenced by stellar flux, equilibrium temperature, and water/biosignature scores. The discussion connects scientific results with educational practice: interdisciplinary astrobiology models offer rich contexts to develop science literacy, scientific reasoning, and analog-based laboratory experiences. Pedagogical recommendations include curriculum development, teacher training, and mission-based learning strategies. The article closes with ethical and communicative notes on claims of life detection and the need for robust evidence frameworks and communication protocols.

Keywords: **B*ioastronomy, Astrobiology, Biosignature, Habitability, Science Educatio***

Article Info
Received: 13 Desember 2025
Revised: 21 Desember 2025
Accepted: 30 Desember 2025
Published: 31 Desember 2025

A. Introduction

Questions regarding the origin and existence of life in the universe have always been one of the fundamental issues in philosophy, science, and even theology. Since the era of Greek philosophers like Democritus to the modern era, humans have continued to ask: does life exist only on Earth, or is it scattered throughout the universe? [1]. With the development

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of science, a new field known as bioastronomy or astrobiology was born, which is an interdisciplinary discipline that examines the origin, distribution, and possible sustainability of life beyond Earth using modern scientific approaches [2], [3].

Advancements in astronomy and observational technology have revolutionized human perspectives on cosmic life. The discovery of thousands of exoplanets through the Kepler and TESS telescopes has proven that our solar system is not the only planetary system [4], [5]. Some of these are even located in the habitable zone, a region that allows for liquid water to exist on the surface [6]. On the other hand, research on extremophiles on Earth shows that life can survive in extreme conditions—such as volcanic heat, polar ice, or deep-ocean pressure—thereby expanding the possibility of life existing beyond Earth [7], [8].

In the realm of education, the issue of bioastronomy has strategic relevance. 21st-century science education is required not only to teach basic concepts but also to build critical thinking skills, problem-solving, science literacy, and global awareness in students [9], [10]. The topic of bioastronomy, which is rich in multidimensional dimensions—covering biology, chemistry, physics, geology, astronomy, to philosophy—can be an ideal vehicle for developing cross-disciplinary learning approaches [11], [12].

Bioastronomy studies do not merely answer cosmological questions but also contribute to the development of science and technology. From a pure science perspective, bioastronomy plays a role in explaining planetary habitability requirements, detecting biosignatures, and understanding cosmic ecosystem dynamics [13], [14]. From a technological perspective, this research drives innovation in observational instruments such as next-generation space telescopes, spectral sensors, as well as manned and unmanned space missions [15], [16].

From an educational perspective, bioastronomy also becomes a learning medium that can spark imagination while instilling scientific skills. The integration of bioastronomy into the science curriculum can strengthen inquiry-based learning and problem-based learning approaches [17], [18]. Through real issues—such as the search for life on Mars, the exploration of Europa and Enceladus, or the discovery of exoplanets—students can be trained to formulate hypotheses, analyze data, and engage in reflective thinking. Thus, bioastronomy not only provides factual knowledge but also trains critical scientific thinking.

Previous studies have extensively examined the scientific aspects of bioastronomy. McKay [13] emphasized the importance of understanding planetary habitability as a basis for the search for life. Lingam and Loeb [5] highlighted the probability of cosmic life using

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mathematical approaches, while Kaltenegger [3] and Seager [2] outlined strategies for detecting exoplanet atmospheres. Cockell [6] and Domagal-Goldman et al. [19] underscored the importance of biosignatures in space missions. Furthermore, recent studies link bioastronomy with educational perspectives. Oliveri et al. [12] showed that astrobiology-based learning can increase high school students' learning motivation. Dijkstra and Goedhart [11] affirmed that global issues such as the search for extraterrestrial life encourage active student participation in class discussions. Vesterinen et al. [20] even emphasized the role of astrobiology as an ideal context for teaching science literacy due to its multidisciplinary nature. However, Schmidt and Frank [21] warned that without proper curriculum integration, students are at risk of experiencing misconceptions.

Nevertheless, research on the integration of bioastronomy into formal education remains limited, especially in developing countries. In Indonesia, studies on bioastronomy are almost non-existent in the school curriculum or national educational literature [22]. Yet, the potential application of bioastronomy as a vehicle for strengthening science literacy is enormous, considering this topic can link science with contemporary global issues. Based on the literature review, there is a research gap between scientific advancements in bioastronomy and its utilization in an educational context. At the international level, a number of studies have attempted to connect astrobiology with science literacy [12], [20]. However, at the national level, the integration of bioastronomy in the Indonesian curriculum remains unexplored. Thus, this conceptual review is important to review the development of bioastronomy while examining its implications for science learning in schools.

B. Method

The research method employed is a systematic literature review with the following stages:

1. Literature Sources

Literature was collected from reputable international and national databases:

- Scopus, Web of Science, SpringerLink, and ScienceDirect were used to search for current astrobiology/bioastronomy articles.
- ERIC, ProQuest, Google Scholar, and SINTA were used to search for articles related to science education and literacy.
- The time range of the literature taken is the last 7 years (2018–2025).

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- Literature types include peer-reviewed journal articles, international proceedings, and official reports from science institutions (such as NASA, ESA, and the SETI Institute) .

2. Inclusion Criteria

- To ensure data relevance, the following inclusion criteria were established:
- The article discusses bioastronomy, astrobiology, or the exploration of life in the universe.
- The article relates the topic to education, science literacy, or learning implications.
- The article is peer-reviewed with full access to methodology and results.
- Written in English or Indonesian.

3. Exclusion Criteria

The exclusion criteria applied were:

- Articles in the form of opinions, editorials, or non-peer-reviewed materials.
- Articles irrelevant to bioastronomy or education (e.g., discussing pure astronomy without life or educational aspects).
- Duplication of search results.

4. Analysis Process

The analysis process was carried out using the PRISMA Flow Diagram with the stages: Identification → Screening of titles/abstracts → Full-text evaluation → Final inclusion. Content analysis was conducted focusing on:

- Main bioastronomy themes (exoplanets, habitability, extremophiles, extraterrestrial life).
- Integration into education (curriculum, science literacy, interdisciplinary learning models).

5. Data Synthesis

Research results were synthesized using a thematic narrative approach. Literature was classified into two main categories: Scientific Conceptual (astrobiology discoveries, bioastronomy) and Educational Implications (learning models, science literacy, curriculum

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strengthening). Comparisons between studies were made to find patterns, gaps, and potential innovations.

6. Validation

Data validation was performed through literature triangulation by comparing findings from various databases. Additionally, peer debriefing (discussions with science education & astronomy experts) and an audit trail were conducted to record the article selection process, criteria, and analysis results to ensure transparency and reproducibility.

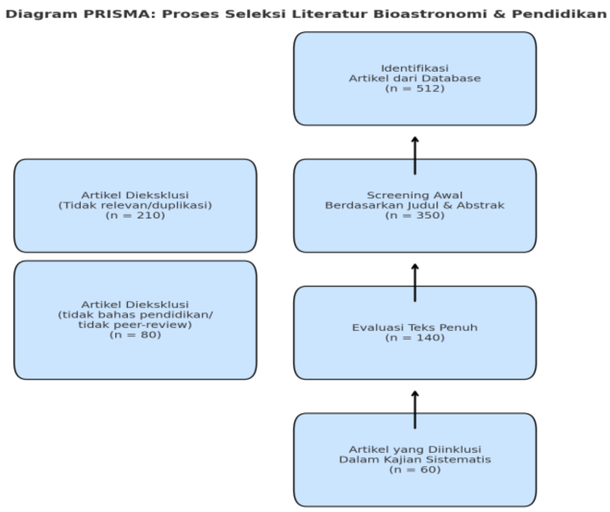

Figure 1. PRISMA Diagram

C. Results and Discussion

1. Literature Review Results

From the literature search process in various databases (Scopus, Web of Science, ScienceDirect, ERIC, and SINTA), 126 relevant articles were obtained. After passing through the screening process based on inclusion-exclusion criteria, the number of articles analyzed further was 38 articles. These articles were categorized into two large clusters.

First, Bioastronomy Science Concepts. This cluster focuses on the exploration of extraterrestrial life, including studies on exoplanets, habitability zones, extremophile microbes, and laboratory simulations related to the origin of life (abiogenesis). Current studies emphasize the analysis of exoplanet atmospheres using next-generation telescopes (e.g.,

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JWST). Research on extremophiles on Earth (e.g., microbes in Mono Lake, Yellowstone, and the Deep Sea) is used as an analog model for life in extreme extraterrestrial environments.

Second, Educational Implications. The literature shows that bioastronomy themes are beginning to be used as an interdisciplinary approach in science learning. The integration of astrobiology in the curriculum has been proven to increase students' science literacy, critical thinking, and curiosity [21], [24]. Several educational studies show that linking astronomy with life issues (life beyond Earth) can increase STEM learning interest in high school and university students [11], [2].

The main findings from this analysis are:

1. Bioastronomy as a bridge of knowledge: Effective in connecting biology, chemistry, and astronomy, making it an ideal vessel to encourage discipline-integration-based learning.
2. Strengthening science literacy: The astrobiology approach helps students understand global issues (e.g., the sustainability of life on Earth and space exploration) more contextually.
3. Research gap: There are still very few studies systematically examining bioastronomy-based learning models in secondary schools or higher education, especially in Indonesia.
4. Implementation potential: Astrobiology literacy can be integrated into the Junior/Senior High School Science curriculum through topics such as exoplanets, microorganisms, and life sustainability.

2. Discussion: Relevance and Curriculum Integration Opportunities

Bioastronomy unites cross-disciplinary concepts and scientific practices such as observation, modeling, data analysis, and argumentation. This makes it highly suitable for inclusion in a science learning framework that emphasizes critical thinking skills and data literacy, in line with 21st-century education policies. Practically, integration can be done at several points in the Science/High School curriculum: (a) Microbiology/biochemistry chapters (extremophiles as case studies of adaptation); (b) Physics/astronomy (exoplanets, habitability conditions); and (c) Cross-topic STEM projects.

For effective implementation, pedagogical approaches must be rooted in strong learning theories:

- Constructivism & Social Construction: Students build meaning through collaborative inquiry tasks with teacher scaffolding [23].
- Inquiry-Based Learning (IBL): Encourages students to formulate hypotheses about biosignature detection and draw evidence-based conclusions.
- Project-Based Learning (PBL): Suitable for long-term projects like "Designing a life search mission" [17].
- Situated Learning: Connecting students with the scientific community through citizen science.
- Argumentation: Using the Claim-Evidence-Reasoning (CER) framework to assess scientific evidence.

3. Bioastronomy-Based Science Literacy Model

This study proposes the "LITAR-Bio" (Integrated Astronomy–Biology Literacy) framework which includes the components:

- Conceptual Content: Habitability, biosignatures, extremophiles.
- Scientific Practices: Observing, data analysis, modeling, argumentation.
- Epistemic Understanding (NOS): Understanding data uncertainty and the role of models.
- Socio-Scientific Issues (SSI): Planetary protection ethics and social implications of exploration.

As a concrete strategy, learning can be designed in 4 meetings: (1) Building initial concepts through a virtual tour to Mars; (2) Laboratory experiments on extremophiles; (3) Simple dataset analysis (transit curves) with CER tasks; and (4) Life search mission planning project. Assessment is carried out using cognitive tests, CER rubrics, and PBL project assessments.

D. Conclusion

This literature review asserts that bioastronomy, as an interdisciplinary field combining biology, chemistry, physics, and astronomy, has great potential to enrich science learning in Indonesia. Conceptually, bioastronomy opens new horizons regarding the possibility of life beyond Earth, utilizing research data on exoplanets, extreme ecosystems, and planetary

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habitability. Meanwhile, educationally, this topic offers a contextual bridge that can foster students' interest, curiosity, and science literacy by presenting the fundamental question: "Are we alone in the universe?".

The integration of bioastronomy in the curriculum can support the strengthening of 21st-century competencies: critical, creative, collaborative thinking, and digital literacy. Through inquiry-based learning, constructivism, and problem-based learning approaches, students not only understand science concepts but also learn to explore evidence, formulate hypotheses, and connect cosmic phenomena with daily life. This research also identifies a research gap that bioastronomy is still rarely used in Indonesian education. Yet, as a frontier science, this field can be a strategic means to build scientific literacy based on a global context. Therefore, the development of a bioastronomy-based science literacy model is crucial to broaden students' horizons while supporting the national curriculum vision.

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