A Comprehensive Review of Exoplanet Biosignatures

Myasar Ismael Amded

mesralasmailpes@gmail.com

Abstract

We present a comprehensive synthesis of exoplanet biosignatures spanning atmospheric (gaseous), surface, and temporal indicators, with an emphasis on contextual, multi-observable assessment. Building on rapid advances in exoplanet characterization—particularly high-precision spectroscopy enabled by current and planned facilities—we review candidate gases (e.g., O_2, O_3, CH_4, N_2O) and alternative volatiles (e.g., NH_3, PH_3, DMS, COS, CH_3Cl), outlining their principal biological sources, dominant sinks, and leading abiotic false-positive pathways. We formalize three evaluation pillars—detectability, survivability, and specificity—and highlight the diagnostic value of thermodynamic and kinetic redox disequilibria (e.g., O_2–CH_4 co-occurrence) as integrative metrics. Beyond gases, we survey surface biosignatures such as the vegetation red edge and pigment-linked polarization, and temporal biosignatures including seasonal modulation of atmospheric composition and phase-dependent photometric variability tied to surface phenology. We discuss observational strategies that combine transmission/emission/reflection spectroscopy with rotational mapping and polarimetry to improve robustness against confounding processes (e.g., photochemistry, volcanism, hazes, and clouds). Finally, we outline probabilistic (Bayesian) frameworks that synthesize multiwavelength data and planetary–stellar context to quantify the likelihood that observed signals are life-driven. This review consolidates current understanding, identifies key degeneracies, and maps observational pathways that can transform ambiguous detections into convergent evidence for inhabited worlds.

Keywords: exoplanets; biosignatures; atmospheric spectroscopy; redox disequilibrium; vegetation red edge; temporal variability; Bayesian inference; false positives.

INTRODUCTION: THE SEARCH FOR LIFE BEYOND THE SOLAR SYSTEM

Over the past thirty years, our grasp of planetary systems outside the Sun's domain has expanded dramatically, driven by the confirmation of more than 5,000 exoplanets (Christiansen 2022). These planets display striking diversity in size, structure, and stellar heating, spanning bodies smaller than Mercury (Barclay et al. 2013) to giants exceeding twice Jupiter's radius (Crouzet et al. 2017). A transformative stage in this field began with the deployment of the James Webb Space Telescope (JWST), which has already provided unparalleled insights into the chemistry and makeup of alien atmospheres (Ahrer et al. 2023; Alderson et al. 2023; Tsai et al. 2023). As atmospheric studies accelerate, review articles serve as essential references for understanding planetary origins, climate systems, chemical cycles, and observable traits (Helling 2019; Jontof-Hutter 2019; Pierrehumbert and Hammond 2019; Shields 2019; Madhusudhan 2019; Wordsworth and Kreidberg 2022; Kempton and Knutson 2024).

Among the detected worlds, a fraction lies within the so-called "habitable zone" (HZ)—a circumstellar region where a geologically active rocky planet with an atmosphere rich in N_2, CO_2, and H_2O could maintain liquid water on its surface (Kasting et al. 1993; Kopparapu et al. 2013, 2014; Kane et al. 2016). Broader definitions extend this zone to include larger super-Earths wrapped in hydrogen-dominated atmospheres with deep oceans, referred to as Hycean planets (Madhusudhan et al. 2021, 2023). Although the presence of liquid water is central to life as we know it, true habitability also depends on other essentials such as accessible energy sources, nutrient cycles, and stable physical and chemical conditions (Cockell et al. 2016; Hoehler et al. 2020).

Assessing whether a planet can host life begins with evaluating the habitability of the star–planet system. The HZ offers a predictive framework for identifying planets that could support surface oceans, enabling active gas exchange between atmosphere and potential biosphere (Kasting et al. 2014). It also helps prioritize planets that may yield surface information through remote observation. This concept, however, was never meant to capture all possible niches for life. For instance, icy satellites—akin to Europa or Enceladus in our solar system—may harbor vast subsurface oceans (Hendrix et al. 2019), though such hidden habitats remain inaccessible to current remote-sensing techniques. The quest to detect extraterrestrial life is at the heart of NASA's Astrobiology Program (Hays et al. 2015) and strongly motivates future observatory concepts, such as the large infrared/optical/UV telescope envisioned by the National Academies to succeed JWST and Hubble (National Academies of Sciences, Engineering, and Medicine 2021). The detection of "biosignatures," signals of life encoded in the spectra of distant atmospheres and surfaces, represents a primary pathway toward answering one of humanity's oldest questions.

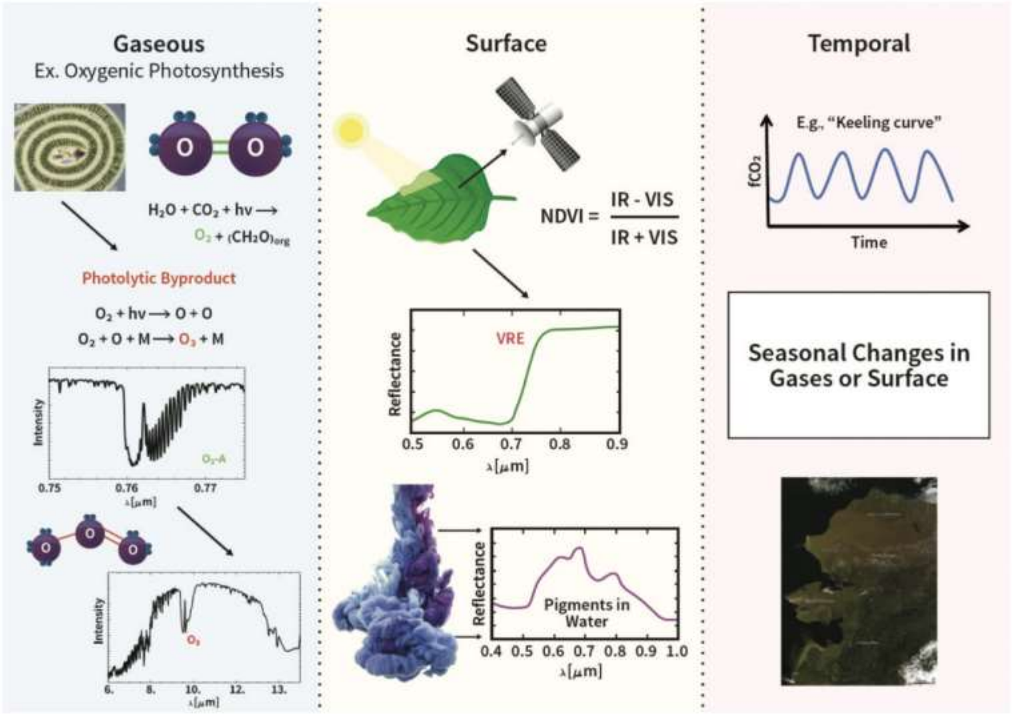

Figure 1. Overview of Biosignatures: Atmospheric (left), Surface (middle), and Temporal (right).

Atmospheric biosignatures refer to volatile molecules and spectrally detectable gases linked to biological activity, such as molecular oxygen (O_2) generated through oxygenic photosynthesis, along with secondary photochemical products like ozone (O_3) formed from O_2 interactions with stellar radiation.

Surface biosignatures involve reflectance features, most notably the “vegetation red edge” (VRE), which arises from the strong absorption of visible light by chlorophyll contrasted with high infrared reflectivity in photosynthetic organisms.

Temporal biosignatures highlight periodic or seasonal changes associated with life processes—for instance, fluctuations in CO_2 levels driven by photosynthetic uptake and the decomposition of organic matter, or cyclical shifts in surface reflectivity (albedo) linked to vegetation growth and decline.This illustration is adapted from Schwieterman (2021) under the Creative Commons Attribution License (CC-BY). Image components credited to NASA and the Encyclopedia of Life (EOL). In general, a biosignature is described as *any material, structure, pattern, or process—or a combination of these—that provides evidence for present or past life and can be distinguished from non-biological origins* (Des Marais and Walter 1999; Des Marais et al. 2008; Hays et al. 2015). When applied to planets beyond the Solar System, the term refers to remotely detectable signals of biological activity that leave an imprint on a planet’s atmosphere or surface. Such signals may manifest as individual gases (or suites of gases), reflectance or surface characteristics, or variations over time in atmospheric or surface properties that are plausibly linked to living systems (Figure 1).

For clarity, this definition excludes markers of technological civilizations, commonly termed *techno signatures* (Tarter 2001, 2006; Wright et al. 2022), which fall outside the scope of this discussion—though overviews of such indicators can be found elsewhere (e.g., Haqq-Misra et al. 2022). It is important to emphasize that any claimed biosignature on an exoplanet must undergo rigorous validation beyond the initial detection to verify a biological cause. For this reason, researchers typically describe them as *potential biosignatures* until sufficient evidence supports their origin as life-driven (Schwieterman et al. 2018a; Meadows et al. 2022). Some scholars remain cautious, questioning whether any remote measurement could definitively demonstrate life without technological input (Smith and Mathis 2023) or critiquing the conventional use of the word “biosignature” in exoplanet studies, suggesting revised definitions (Gillen et al. 2023). Although these debates are valuable and warrant continued dialogue (Malaterre et al. 2023), our goal here is to summarize the main categories of exoplanet biosignatures as treated in the scientific literature.

Key Characteristics of a Strong Biosignature

According to Meadows (2017) and Meadows et al. (2018b), an effective biosignature must demonstrate three main qualities: **detectability, persistence, and distinctiveness**.

- **Detectability** concerns whether the molecule or feature has optical properties—such as absorption, scattering, or emission—that allow it to leave a measurable imprint on light passing through, reflecting off, or radiating from the planet. For instance, molecular oxygen (O_2) exhibits a well-known absorption band at 0.76 µm that is clearly visible in Earth's reflected spectrum (Figure 2).
- **Persistence (or survivability)** addresses the ability of the biosignature to withstand destructive planetary or stellar processes, such as photodissociation by ultraviolet radiation from the host star. For a biosignature to be meaningful, it must reach and sustain concentrations sufficient to alter the observed spectrum, which depends on reaction rates, photochemical stability, and other atmospheric processes. However, this resilience can complicate interpretation, as even minor abiotic production mechanisms may, over long timescales, lead to detectable accumulation.
- **Distinctiveness (specificity)** evaluates whether the signal can be reliably distinguished from non-biological origins. The context is crucial here. On Earth, for example, methane (CH_4) exists in marked thermodynamic and kinetic disequilibrium with the planet's oxygen-rich, temperate atmosphere—an arrangement strongly suggestive of biological activity (Sagan et al. 1993). Conversely, in the gas giants of our Solar System, methane is abundant but arises naturally as a stable chemical outcome in hydrogen-dominated atmospheres at high temperatures (Lodders and Fegley 2002; Moses et al. 2013).

In this section, we outline the range of suggested biosignatures for exoplanets, discussing their potential biological sources, detectable characteristics, and abiotic processes that might mimic them. For readers seeking more detail, extensive discussions can be found in the references cited here as well as in earlier in-depth reviews (Seager et al. 2012; Seager and Bains 2015; Kaltenegger 2017; Grenfell 2017; Schwieterman et al. 2018a; Catling et al. 2018;

Fujii et al. 2018; Walker et al. 2018). Our goal is to highlight developments and publications that have appeared since those prior surveys, while still establishing a clear conceptual background for each biosignature introduced.

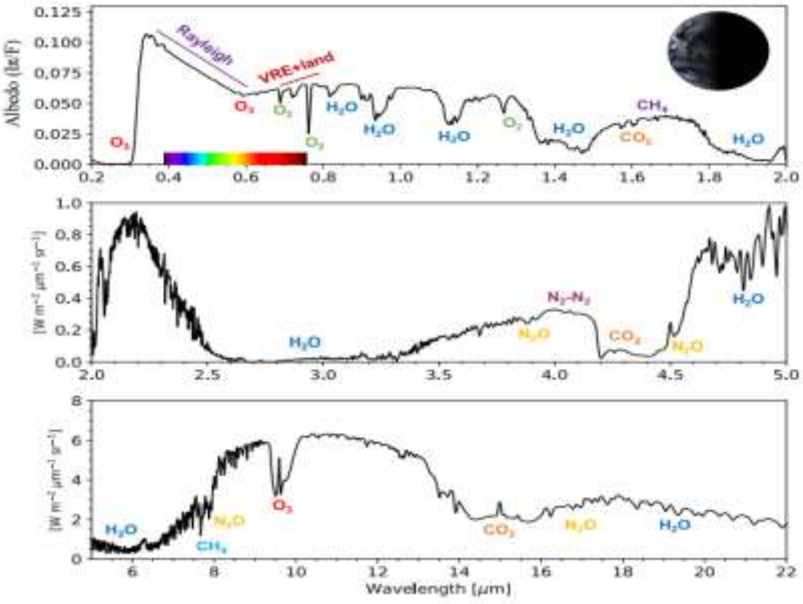

Figure 2. Modeled Earth Spectrum (0.2–22 µm) at Half-Phase Illumination

This synthetic spectrum illustrates a range of atmospheric and surface signals, including the biosignature gases O_2, O_3, and CH_4; the "vegetation red edge" (VRE) reflectance feature; and habitability-related gases such as H_2O, CO_2, and N_2. Rayleigh scattering also appears, serving as an indicator of atmospheric pressure.

- **Top panel:** Apparent spectral albedo from 0.2–2 µm (ultraviolet, visible, and near-infrared) under quadrature geometry, dominated by reflected sunlight.
- **Middle panel:** Near-infrared output (2–5 µm) expressed as spectral radiance (W m^{-2} μm^{-1} sr^{-1}), showing contributions from both reflected and emitted light.
- **Bottom panel:** Thermal infrared region (5–22 µm) expressed in spectral radiance, highlighting planetary emission features.

The spectrum was generated with the Virtual Planetary Laboratory's three-dimensional Earth spectral model (Robinson et al. 2011; Schwieterman et al. 2015b). The version shown here is adapted from Schwieterman et al. (2018a) under a CC-BY license, with modifications that include extra labels for gas absorption bands, an inset showing Earth in half illumination, and a color bar marking the visible wavelength domain.

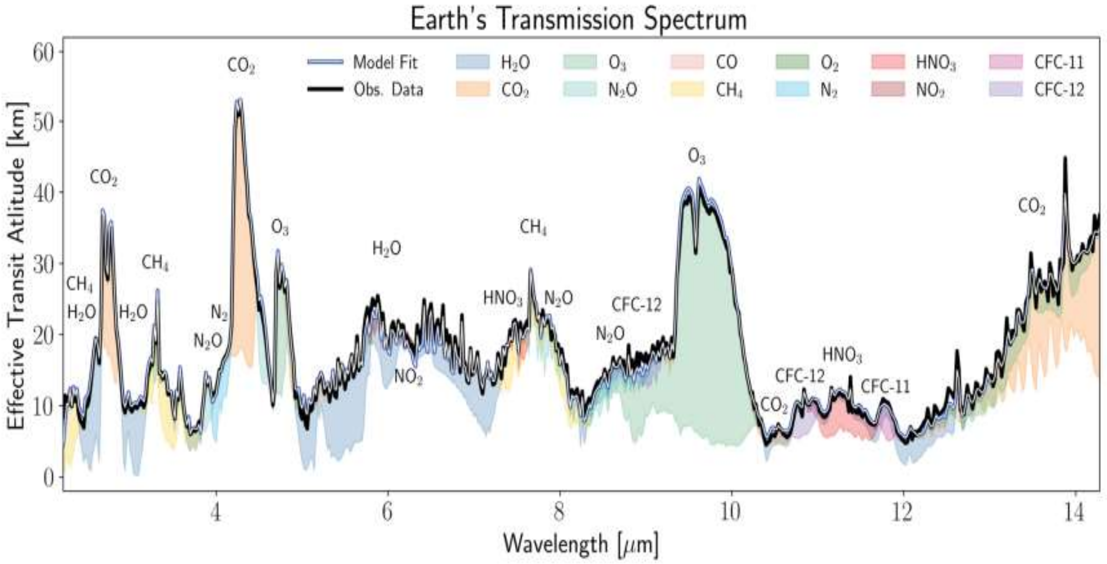

Figure 3. Infrared Transmission Spectrum of Earth (2–15 μm, Cloud-Free)

Shown here is Earth's clear-sky transmission spectrum in the infrared range, originally presented by Macdonald and Cowan (2019, black curve) and reproduced with a spectral fit generated by the SMARTER retrieval framework (blue curve; Lustig-Yaeger et al. 2023).

This spectrum highlights several categories of atmospheric constituents:

- **Habitability tracers:** CO_2 absorption at 2.7, 4.3, and 15 μm; H_2O at 6 μm; and N_2 at 4.2 μm.
- **Biosignature gases:** CH_4 at 3.3 and 7.7 μm; O_3 at 4.7 and 9.7 μm; and N_2O at 4.0, 7.7, and 8.5 μm.
- **Anthropogenic pollutants:** chlorofluorocarbons CFC-11 (CCl_3F) near 11.8 μm, CFC-12 (CCl_2F_2) at 10.8 μm, and nitrogen dioxide (NO_2) around 6.2 μm.

This illustration is adapted from Lustig-Yaeger et al. (2023) and is distributed under the Creative Commons Attribution License (CC-BY).

ATMOSPHERIC (GASEOUS) BIOSIGNATURES

Atmospheric or gaseous biosignatures are volatile compounds produced by biological activity that imprint identifiable spectral features in a planet's reflected, emitted, or transmitted light (Schwieterman et al., 2018). Classic candidates include oxygen (O_2) and its photochemical product ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and mixtures of gases in strong thermodynamic disequilibrium such as O_2–CH_4 (Seager et al., 2016; Schwieterman et al., 2018). Interpreting these signals relies on three pillars—detectability via distinct absorption/emission bands, survivability against stellar/planetary destruction pathways, and specificity for separating biotic from abiotic production—each evaluated within the planetary–stellar context to avoid false positives (Meadows et al., 2018; Catling et al., 2018). For example, CH_4 in Earth's O_2-rich atmosphere is difficult to maintain abiotically and thus indicative of life, whereas CH_4 in giant planets commonly arises from equilibrium chemistry in H_2-dominated atmospheres (Catling et al., 2018; Meadows et al., 2018).

Oxygen and Ozone (O_2 and O_3)

Molecular oxygen is a classic atmospheric biosignature because steady, high abundances on temperate rocky planets are difficult to sustain abiotically; on Earth, O_2 is predominantly sourced by oxygenic photosynthesis, commonly summarized as:

$$6\,\mathrm{CO_2} + 6\,\mathrm{H_2O} + \text{photons} \;\longrightarrow\; \mathrm{C_6H_{12}O_6} + 6\,\mathrm{O_2}.$$

Ozone arises photochemically from O_2 via the Chapman reactions, which link O_2 and O_3 observables:

$$\mathrm{O_2} + h\nu\ (\lambda < 240\ \mathrm{nm}) \rightarrow 2\,\mathrm{O}, \mathrm{O} + \mathrm{O_2} + M \rightarrow \mathrm{O_3} + M,$$
$$\mathrm{O_3} + h\nu \rightarrow \mathrm{O_2} + \mathrm{O}, \mathrm{O} + \mathrm{O_3} \rightarrow 2\,\mathrm{O_2}.$$

Detectability relies on strong bands such as the O_2 A-band at 0.76 µm and O_3 features near 9.6 µm and in the UV Hartley–Huggins system, while survivability depends on photochemical and surface sinks balanced by sustained sources (Meadows et al., 2018; Schwieterman et al., 2018). Specificity requires ruling out abiotic pathways that can generate O_2/O_3, including CO_2 photolysis and subsequent recombination:

$$\mathrm{CO_2} + h\nu \rightarrow \mathrm{CO} + \mathrm{O}, \mathrm{O} + \mathrm{O} + M \rightarrow \mathrm{O_2} + M, \mathrm{O} + \mathrm{O_2} + M \rightarrow \mathrm{O_3} + M,$$

which are favored under dry, H-poor atmospheres with strong UV and weak reducing fluxes. Consequently, O_2/O_3 must be interpreted within a full planetary–stellar context (e.g., water inventory, surface oxidation state, UV spectrum) to minimize false positives (Catling et al., 2018; Meadows et al., 2018; Seager et al., 2016; Schwieterman et al., 2018).

Methane (CH_4)

Methane is frequently highlighted as a potential atmospheric biosignature due to its short photochemical lifetime in oxidizing atmospheres and its strong association with biological processes. On Earth, the primary biological pathway for methane production is microbial methanogenesis, often represented by the reduction of carbon dioxide with hydrogen:

$$\mathrm{CO_2} + 4\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\mathrm{H_2O}.$$

Additionally, certain anaerobic archaea produce methane through fermentation of acetate:

$$\mathrm{CH_3COOH} \longrightarrow \mathrm{CH_4} + \mathrm{CO_2}.$$

These biogenic sources contrast with abiotic pathways such as serpentinization, where water reacts with olivine-rich rocks to generate hydrogen, which subsequently reduces carbon-bearing compounds to methane:

$$\begin{aligned}&(\mathrm{Mg,Fe})_2\mathrm{SiO_4} + \mathrm{H_2O} \longrightarrow \text{serpentine} + \text{magnetite} + \mathrm{H_2},\\&\mathrm{CO_2} + 4\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\mathrm{H_2O}.\end{aligned}$$

Methane's detectability arises from its strong absorption bands at 3.3 µm and 7.7 µm, making it observable in exoplanet spectra when present at sufficient abundances (Schwieterman et al., 2018). However, because abiotic processes can also yield methane, robust biosignature interpretation requires contextual evidence, particularly when CH_4 coexists with oxidants like O_2 or O_3, creating a pronounced redox disequilibrium difficult to sustain abiotically (Catling et al., 2018; Meadows et al., 2018). In this disequilibrium framework, the simultaneous detection of CH_4 and O_2 is considered one of the strongest indicators of biological activity on a rocky exoplanet (Seager et al., 2016; Schwieterman et al., 2018).

Nitrous Oxide (N_2O)

Nitrous oxide is considered a significant candidate biosignature gas because of its strong association with microbial metabolism and its distinctive spectral features. On Earth, N_2O is primarily produced by microbial denitrification, where nitrate and nitrite are reduced under low-oxygen conditions, and by nitrification as a byproduct of ammonia oxidation. A simplified net denitrification pathway can be expressed as:

$$2\,\mathrm{NO_3^-} + 10\,\mathrm{e^-} + 12\,\mathrm{H^+} \;\longrightarrow\; \mathrm{N_2O} + 6\,\mathrm{H_2O}.$$

An additional step can lead to complete reduction to molecular nitrogen:

$$\mathrm{N_2O} + 2\,\mathrm{e^-} + 2\,\mathrm{H^+} \;\longrightarrow\; \mathrm{N_2} + \mathrm{H_2O}.$$

Abiotic sources of N_2O are relatively limited compared to biogenic processes. Lightning activity and high-energy particle interactions in the upper atmosphere can generate trace amounts, but these are typically insufficient to accumulate to spectrally detectable levels (Schwieterman et al., 2018). This relative scarcity of robust abiotic production pathways strengthens the case for N_2O as a biosignature.

From an observational perspective, N_2O has notable infrared absorption features at 4.5 µm, 7.8 µm, and 8.5 µm, which could be detected in exoplanetary spectra with advanced instruments (Catling et al., 2018). However, atmospheric context remains critical: the detectability and stability of N_2O depend on factors such as photolysis rates under stellar UV flux and the presence of competing sinks. When found alongside other biologically associated gases like O_2 or CH_4, N_2O can contribute to a stronger multi-gas biosignature framework (Meadows et al., 2018; Seager et al., 2016).

Alternative biosignature gases

Beyond classical species (O_2, O_3, CH_4, N_2O), several volatile compounds have been advanced as *alternative* biosignatures, motivated by their strong biological production routes on Earth and potentially distinctive spectra. Candidates include reduced nitrogen and phosphorus species such as ammonia (NH_3) and phosphine (PH_3), organosulfur gases like dimethyl sulfide (DMS) and carbonyl sulfide (COS), and organohalogens (e.g., methyl chloride, CH_3Cl). In H_2-dominated atmospheres, NH_3 is especially promising because it can be produced biotically yet is rapidly destroyed photochemically, requiring sustained sources to remain detectable; concomitant redox disequilibria (e.g., NH_3 with oxidants) can strengthen the biological interpretation (Seager et al., 2016; Catling et al., 2018). PH_3 has been proposed as a potential indicator of anaerobic metabolism, though its assessment is highly context-dependent due to uncertain abiotic yields and photochemical lifetimes (Seager et al., 2016; Catling et al., 2018). Biogenic sulfur gases such as DMS and COS are emitted by marine microbiota and have mid-infrared vibrational bands that, in principle, could be probed in transmission or emission spectra; however, volcanism and photochemistry can generate sulfur species abiotically, demanding careful false-positive screening (Schwieterman et al., 2018; Catling et al., 2018). CH_3Cl and related organohalogens—produced by microbes and plants—also present recognizable mid-IR features but may suffer from competing abiotic pathways and low expected mixing ratios on many worlds (Seager et al., 2016; Schwieterman et al., 2018).

Consequently, modern frameworks treat these gases within a *contextual, multi-gas* approach that weighs detectability, survivability, and source specificity against planetary environment, stellar UV spectrum, and plausible abiotic production mechanisms (Meadows et al., 2018; Catling et al., 2018).

Table 1. Abundant and/or Prominent Earth Atmospheric Biosignature Molecules

Biosignature	Production Environment	Concentration on Earth	False Positives and Secondary Outcomes	Main Spectral Features (µm) (strongest bolded)	Citation
Oxygen (O_2)	Photic terrestrial and marine environments; produced by cyanobacteria, algae, and plants via oxygenic photosynthesis	20.95%	• Low non-condensable inventories (Wordsworth & Pierrehumbert, 2014) • Ocean loss (Luger & Barnes, 2015; Tian, 2015) • CO_2 photolysis (Domagal-Goldman et al., 2014; Gao et al., 2015; Harman et al., 2015) • High CO_2/H_2O inventories or very low initial H_2O (Krissansen-	O_2 at 0.63, 0.69, **0.76**, 1.27; O_4 CIA at 0.445, 0.475, 0.53, 0.57, 0.63, 1.06, **1.27**, 6.4	Meadows (2017); Meadows et al. (2018b)

			Totton et al., 2021) • Atmospheric exchange/exogenous delivery (Felton et al., 2022)		
Ozone (O_3)	Photochemical product of O_2; influenced by H_2O, SO_2, CO_2	0.07 ppm	• Abiotic O_2 or CO_2 can generate O_3 features (Domagal-Goldman et al., 2014; Gao et al., 2015; Harman et al., 2015)	**0.25** (Hartley), 0.4–0.7 (Chappuis), 2.6, 4.7, **9.65**, 14.6	Meadows et al. (2018b); Kozakis et al. (2022)
Methane (CH_4)	Wetlands, rice paddies, livestock emissions, biomass burning & decomposition (biotic and abiotic)	1.90 ppm	• Serpentinization • Fischer–Tropsch reactions • High-temperature mantle processes • Equilibrium chemistry in giant planet atmospheres	1.65, 2.3–2.4, **3.3**, **7.7** (broad)	Etiope & Sherwood-Lollar (2013); Thompson et al. (2022)
Nitrous Oxide (N_2O)	Marine settings, some soils; produced via	0.33 ppm	• Lightning and NO_x chemistry • Abiotic processes such as	1.5, 1.6, 1.7, 1.8, 2.3, 2.6, 2.9, 3.7,	Schwieterman et al. (2018);

	denitrification and nitrification		chemodenitrification and StEPs	4.0, **4.5**, **7.8**, **8.5**, 17	Catling et al. (2018)

SURFACE AND TEMPORAL BIOSIGNATURES

Surface biosignatures are spectral, photometric, or polarimetric features imprinted by life on a planet's surface, while temporal biosignatures are time-variable signals—of either atmospheric composition or surface reflectance—whose periodicity and amplitude are consistent with biological activity and difficult to reproduce abiotically in the same context (Schwieterman et al., 2018). The canonical surface example is the vegetation red edge (VRE): a sharp increase in reflectance longward of ~0.70 µm caused by strong chlorophyll absorption in the red (≈0.45 and ≈0.67 µm) and efficient near-infrared scattering by leaf internal structures, producing a diagnostic spectral "edge" observable in disk-integrated light under suitable clouds and viewing geometry (Seager et al., 2005; Arnold et al., 2002). Extensions of this concept consider alternative photosystems and pigments—e.g., bacteriochlorophylls or retinal—whose peak absorptions could shift the "edge" to different wavelengths on planets orbiting redder stars, altering broad-band colors and reflectance slopes (Schwieterman et al., 2018). Beyond scalar reflectance, chiral biological matter can imprint circular polarization features near pigment bands; weak but structured circular polarization, if observed at planetary scale, would provide complementary evidence for homochirality in biotic macromolecules (Sparks et al., 2009).

Geometric and environmental effects modulate these signals. Clouds, aerosols, and surface mosaics dilute or mask spectral edges, while bidirectional reflectance distribution function (BRDF) effects and specular "glint" from liquid surfaces can reshape phase-dependent spectra and light curves (Robinson et al., 2010; Cowan et al., 2009). Simple vegetation indices used in terrestrial remote sensing illustrate the principle: the normalized difference vegetation index (NDVI),

$$\mathrm{NDVI} = \frac{R_{\mathrm{NIR}} - R_{\mathrm{Red}}}{R_{\mathrm{NIR}} + R_{\mathrm{Red}}},$$

Tracks fractional vegetation cover through the red–NIR contrast that underlies the VRE and, in principle, could be generalized to exoplanet disk-integrated photometry if photometric precision and spectral placement are adequate (Schwieterman et al., 2018; Seager et al., 2005).

Temporal biosignatures exploit variability arising from biological cycles. On Earth, seasonal drawdown and release of CO_2 and O_2 by photosynthesis and respiration produce repeatable atmospheric oscillations that are spatially and temporally coherent with land-hemisphere phenology; analogous modulations in CH_4 and N_2O also occur with ecosystem activity (Schwieterman et al., 2018). Surface-driven temporal signals include seasonal changes in broadband albedo and color as vegetation greens and senesces, snow/ice advances and retreats, and soils wet and dry—patterns that imprint periodic photometric variability at the planetary rotation and orbital timescales (Cowan et al., 2009). Rotational mapping (light-curve inversion) has been shown, in Earth analog studies, to recover longitudinal maps of oceans and continents and to diagnose surface heterogeneity, providing context to disambiguate biological from abiotic variability (Cowan et al., 2009; Robinson et al., 2010). Interpreting temporal biosignatures requires careful control for false positives: purely abiotic drivers (e.g., seasonally varying haze, volcanic aerosol injection, or cloud belts tied to circulation) can mimic periodic signals, but multiwavelength phase curves, polarization, and joint gas–surface time series help distinguish mechanisms when analyzed within a self-consistent planetary–stellar framework (Schwieterman et al., 2018; Seager et al., 2005).

CONCLUSIONS

Earth's biosphere, dominated by oxygenic photosynthesis, has imprinted a lasting and unmistakable signal on the planet's remote spectrum. Should inhabited worlds exist elsewhere, their biological systems could likewise transform atmospheric chemistry and generate distinctive spectral features detectable from afar. In this work, we have summarized the range of candidate exoplanet biosignatures, examining their sources and sinks, observational manifestations, and potential abiotic impostors. Establishing whether a given signal genuinely represents life requires full planetary context, as no single marker in isolation is expected to serve as definitive proof.

Our discussion has placed particular focus on gaseous biosignatures, since current and near-future observational capabilities are beginning to access these atmospheric signals. These include gases prevalent on Earth today—O_2, O_3, CH_4, and N_2O—as well as trace species biologically generated in small amounts on modern Earth, such as dimethyl sulfide ($(CH_3)_2S$), methyl chloride (CH_3Cl), phosphine (PH_3), and isoprene (C_5H_8), which could reach higher abundances under different planetary conditions. Over geologic time, Earth's shifting redox state has strongly influenced the levels of biogenic gases, particularly CH_4 and N_2O. Disequilibria in thermodynamic and kinetic systems remain powerful diagnostics for identifying possible life-related processes.

In addition to atmospheric evidence, surface indicators such as the vegetation red edge and temporal signals like seasonal variations in atmospheric composition may provide complementary confirmation of biological activity, though they are generally more challenging to detect. Bayesian and other probabilistic frameworks are emerging as tools to enhance the rigor of biosignature interpretation, and further methodological advances are ongoing. Ultimately, the search for extraterrestrial life represents a profound scientific endeavor, and we are fortunate to live at a moment in history when the tools to pursue it are within reach.

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