Molecular architecture of life in non-terrestrial environments: Between physicochemical constraints and nature's ingenious design

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Abstract. This work explores the molecular foundations of life in non-terrestrial environments, focusing on how physicochemical constraints shape the possible architectures of living systems beyond Earth. It examines whether life's molecular organization - carbon-based and water-dependent on Earth - is a contingent outcome of local environmental parameters or a universal expression of chemical self-organization. Drawing from systems chemistry and astrobiology, the discussion highlights that, while the fundamental laws of chemistry remain constant, the structural and functional possibilities of biomolecules may vary dramatically across alternative solvents and planetary contexts. Examples include the potential for silicon-based backbones or ammonia-driven biochemical processes under distinct thermodynamic equilibria. Ultimately, this analysis argues that life's emergence depends not on specific elements, but on the capacity of molecular networks to achieve dynamic stability, energy dissipation, and autocatalytic self-organization. By examining these possibilities, the paper underscores that nature's ingenuity in constructing living systems is an adaptive response to environmental constraints, not a singular terrestrial phenomenon.

Key Words: alternative solvents, astrobiology, carbon chemistry, chemical evolution, molecular architecture, non-terrestrial life, physicochemical constraints, self-organization, systems chemistry.

The question of how nature might construct the molecular foundations of living systems in an environment different from that of Earth lies at the intersection of astrobiology, chemistry, and evolutionary theory (Petrescu-Mag 2009). Understanding whether life's molecular architecture is a contingent product of Earth's conditions or a universal outcome of chemical self-organization is central to assessing the potential diversity of life in the universe.

On Earth, biological systems are based almost exclusively on carbon chemistry, with water serving as the universal solvent and a limited set of bioessential elements (C, H, O, N, P, and S) forming the core of biomolecular structures (Persson & Persson 2018; Westall & Brack 2018; Kacar et al 2020; Mondal & Bagchi 2022). This combination has proven extraordinarily versatile, enabling the emergence of nucleic acids, proteins, lipids, and polysaccharides - molecules capable of self-replication, catalysis, and compartmentalization (Westall & Brack 2018; Ando et al 2021; Mondal & Bagchi 2022; Peters et al 2023). However, these molecular configurations are the result of specific environmental parameters: moderate temperature and pressure ranges, a stable hydrosphere, and an oxidizing atmosphere (Winter 2017; Ando et al 2021; Knop et al 2022; Vilović et al 2023).

In alternative planetary contexts, such as the methane-ethane lakes of Titan (Petrescu-Mag et al 2011; Petrescu-Mag & Gavriloaie 2018), the high-pressure ice environments of Europa (Botha et al 2018), or the acidic clouds of Venus, the same fundamental laws of chemistry would still apply, but their emergent structures could diverge profoundly from terrestrial biochemistry. For instance, silicon-based frameworks, although less flexible than carbon in forming stable, diverse bonds, could under certain temperature and solvent conditions yield polymeric backbones capable of sustaining informational complexity. Likewise, ammonia, methane, or formamide might act as solvents facilitating biochemical reactions at different thermodynamic equilibria.

From a systems chemistry perspective, the formation of life-like entities depends less on the specific atoms involved and more on the capacity of molecular networks to exhibit dynamic stability, energy dissipation, and autocatalytic feedback loops. Nature's "architectural ingenuity" thus derives not from arbitrary creativity, but from exploiting the full spectrum of physicochemical possibilities available under given constraints. The human imagination, although conceptually broad, remains limited by anthropocentric reference points, as our models of life are by necessity shaped by terrestrial experience.

Consequently, the study of non-terrestrial molecular architectures is not merely speculative but fundamental to refining our understanding of what constitutes "life." It challenges the assumption that carbon-water biochemistry is the only viable pathway and opens the door to a broader conception of biological organization. Nature's capacity to reorganize matter into self-sustaining systems, regardless of context, may ultimately prove to be the most compelling demonstration of its evolutionary and chemical ingenuity.

Conflict of Interest. The authors declre that there is no conflict of interest.

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