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Review Article

Boron as a chemical editor: dynamic selection of sugars in prebiotic environments

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Abstract: The prebiotic formation and persistence of carbohydrates remain central challenges in origin-of-life chemistry owing to their instability and structural diversity in aqueous environments. Among potential stabilizing agents, boron species—primarily boric acid and borate—exhibit a unique capacity to form reversible, stereoselective complexes with cis-diol-containing molecules, including sugars and low-molecular-weight polyols. Here we examine the coordination chemistry of boron–diol interactions and explore their implications for prebiotic chemical evolution. By preferentially stabilizing specific sugar configurations, particularly furanose forms, boron may bias the composition of prebiotic mixtures, acting as a primitive chemical "editor." These dynamic interactions—encompassing mono- and diester formation, as well as higher-order assemblies—are modulated by environmental factors such as pH and evaporative concentration. We propose that boron-mediated complexation constitutes a form of thermodynamic selection that enriches biologically relevant carbohydrates, including ribose, while disfavoring less stable isomers.

Keywords: prebiotic chemistry, boron chemistry, borate–diol interactions, ribose stabilization, cis-diol complexation, dynamic covalent chemistry, chemical evolution, thermodynamic selection, origin of life, carbohydrate chemistry

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Boron–diol interactions provide a chemically plausible mechanism for selective stabilization within complex prebiotic mixtures [1–3]. In aqueous environments, boron exists predominantly as boric acid and its conjugate base, borate, with speciation governed by a pK_a of ~9.2. The tetrahedral borate species exhibits enhanced affinity for vicinal diols, forming cyclic esters through coordination to adjacent hydroxyl groups [1–4]. These interactions are highly sensitive to diol geometry, favoring cis-configured hydroxyl groups and selectively stabilizing furanose sugars such as ribose.

The resulting complexes are moderate in strength (10^1–10^4 M^{-1}) yet kinetically labile, enabling rapid exchange and continuous equilibration within chemically diverse mixtures. Beyond simple chelation, borate can form bridging interactions between multiple diol-containing species, generating transient networks that reduce molecular mobility and introduce an emergent level of organization [3–7]. Crucially, borate ester formation is fully reversible, allowing environmental fluctuations—including pH variation and wet–dry cycling—to dynamically reshape complex distributions.

We argue that, under such conditions, boron-mediated complexation operates as a form of thermodynamic selection. Rather than directing specific reaction pathways, boron biases equilibrium populations toward geometrically and electronically compatible structures. In this way, boron may act as a primitive chemical "editor," constraining prebiotic chemical space and promoting the persistence of biologically relevant sugars [1,3,4,8].

1. The problem of sugar selection in prebiotic chemistry

The prebiotic synthesis of carbohydrates generates highly complex mixtures characterized by structural diversity, instability and rapid interconversion. Classical reactions such as the formose reaction produce broad distributions of sugars and degradation products, with little inherent selectivity toward biologically relevant species [9–11]. Ribose, despite its central role in contemporary biology, is particularly unstable under alkaline conditions and readily decomposes [12–14].

This lack of selectivity presents a fundamental challenge: how can specific molecular scaffolds emerge from chemically heterogeneous environments in the absence of enzymatic control? Proposed solutions—including mineral templating, phosphorylation and environmental cycling—offer plausible routes to partial selection, but often rely on narrowly defined conditions or fail to capture the intrinsically dynamic nature of prebiotic systems [15,16].

We argue that reversible molecular interactions, rather than irreversible synthetic pathways alone, may have played a central role in constraining chemical space. In this framework, selection emerges at the level of equilibrium, with transient stabilization mechanisms biasing molecular populations toward compatible structures.

Recent experimental work further refines this view by demonstrating that borate does not increase the peak yield of ribose, but instead suppresses its degradation, leading to enhanced accumulation over time [12, 13]. This distinction indicates that boron-mediated selection operates primarily through differential stability rather than preferential synthesis. Rather than directing the formation of ribose, boron extends its lifetime within dynamic reaction networks, thereby biasing chemical composition over time.

2. Boron in early Earth environments: availability and speciation

Boron is geochemically plausible in a range of prebiotic settings, including evaporitic deposits, hydrothermal systems and localized continental environments. Its distribution reflects its incompatibility in rock-forming minerals, leading to enrichment in evolved crustal settings and evaporative basins. Although the extent of boron availability on the early Earth remains debated, evidence from ancient sediments and boron-bearing minerals suggests that localized boron-rich environments were likely present [17,18].

In aqueous solution, boron exists primarily as boric acid and borate, with speciation governed by pH (pKa $\approx$ 9.2). This equilibrium is highly sensitive to environmental conditions, including mineral buffering, evaporation and ionic composition. Unlike typical Brønsted acids, boric acid functions as a Lewis acid, forming tetrahedral borate upon hydroxide coordination [1–8]. This structural transition is critical, as the tetrahedral borate species exhibits enhanced affinity for vicinal diols, enabling selective interactions with carbohydrate-like molecules [5,7].

Importantly, plausible prebiotic environments were unlikely to be static, but instead characterized by spatiotemporal heterogeneity in pH, solute concentration and water activity. Such fluctuations—arising from processes such as evaporation, fluid mixing and wet–dry cycling—would have dynamically modulated boron speciation and, consequently, its reactivity. Under these conditions, boron–diol interactions would not be constant but continuously redistributed, linking environmental variability to chemical selection processes [1, 4,8].

3. Fundamental chemistry of boron–diol interactions

Boron interacts selectively with cis-diols, forming cyclic esters through coordination to adjacent hydroxyl groups. The stability of these complexes depends on diol geometry, conformational preorganization and solution conditions. Five-membered furanose sugars, including ribose, present favorable binding motifs and are therefore preferentially stabilized relative to less compatible isomers or open-chain forms [16,19,20].

These interactions are moderate in strength (10^1–$10^4\,M^{-1}$) yet kinetically labile, enabling rapid association–dissociation and continuous exchange within complex mixtures. Consequently, boron–diol chemistry operates under conditions of dynamic equilibration, allowing the system to sample multiple binding configurations while favoring thermodynamically stable complexes [20–22].

Beyond simple chelation, borate can form bridging interactions between multiple diol-containing molecules, generating transient networks and higher-order assemblies (Figure 1). Such interactions reduce molecular mobility and effectively partition mixtures into bound and unbound populations, introducing an emergent level of organization within otherwise disordered systems [1,3–6].

Crucially, borate ester formation is fully reversible, placing these interactions within the framework of dynamic covalent chemistry. Environmental perturbations—including pH shifts, concentration changes and wet–dry cycles—continuously redistribute boron–diol complexes [1,3,4,7]. Under these conditions, stability and exchange act in concert, enabling selective persistence of compatible structures over time.

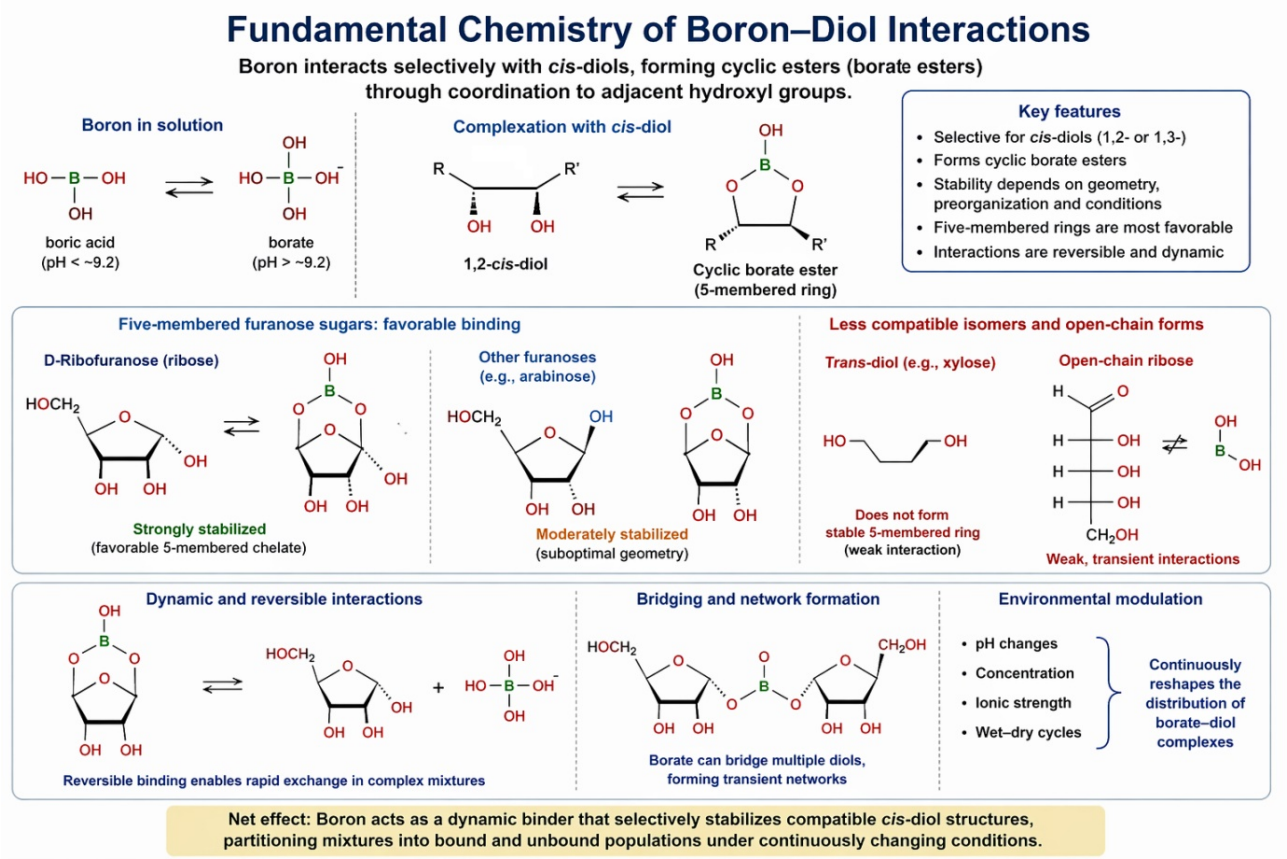

Figure 1. Fundamental chemistry of boron–diol interactions. Boron selectively binds cis-diols to form cyclic borate esters through coordination to adjacent hydroxyl groups. The stability of these complexes depends on diol geometry and is enhanced in conformationally preorganized structures. Five-membered furanose sugars, such as ribose, provide optimal binding motifs and are preferentially stabilized. Less compatible isomers and open-chain forms exhibit weaker and more transient interactions with boron. These reversible interactions enable dynamic selection, biasing molecular populations toward structurally favorable cis-diol-containing sugars

4. Boron as a thermodynamic selector ("*chemical editor*")

We argue that boron-mediated complexation operates as a form of thermodynamic editing, in which reversible binding selectively stabilizes compatible molecular structures while allowing others to dissipate. In this framework, selection arises not from directed synthesis but from differential persistence within dynamically equilibrating systems.

This process differs fundamentally from catalytic control. Rather than accelerating specific reaction pathways, boron biases equilibrium populations by preferentially stabilizing molecules that satisfy geometric and electronic criteria for complexation. In carbohydrate mixtures, this manifests as the stabilization of cis-diol-containing sugars, particularly furanose forms, relative to less favorably configured isomers [3,23,24].

Recent experimental studies further clarify this mechanism by demonstrating that borate does not increase the peak yield of ribose, but instead suppresses its degradation, leading to enhanced accumulation over time [12,13]. This distinction underscores that boron-mediated selection operates primarily through differential stability rather than preferential synthesis.

Under fluctuating environmental conditions, such as drying–wetting cycles, this selection process becomes iterative. Less stable complexes dissociate during perturbation, while more favorable structures persist and accumulate [3,4,25]. The result is a progressive biasing of chemical composition over time, driven by repeated cycles of stabilization and exchange rather than by specific synthetic pathways.

This conceptual framework aligns with broader models of prebiotic chemistry in which selection emerges from physicochemical constraints rather than encoded information, suggesting that dynamic, reversible interactions can act as primitive selectors in complex chemical systems [8,26–28].

5. Implications for the emergence of ribose and early biomolecules

The preferential stabilization of ribose by borate has been experimentally demonstrated, but its implications extend beyond simple preservation [12,13]. By constraining the accessible pool of sugars, boron-mediated selection can reshape downstream reaction networks, influencing processes such as phosphorylation, nucleoside formation and polymerization.

Importantly, this mechanism does not require the exclusive production of ribose. Instead, it operates through relative enrichment, increasing the persistence and availability of ribose compared with competing species (Figure 2). Such biasing of molecular populations may be sufficient to shift reaction pathways toward biologically relevant outcomes, even in chemically heterogeneous environments [16,20–22].

More broadly, boron-mediated complexation provides a mechanism by which environmental conditions can be translated into molecular-level selection. Through its sensitivity to pH, concentration and hydration state, boron effectively couples geochemical dynamics to the stability and distribution of organic molecules. In this sense, boron may act as a mediator between environmental variability and emergent chemical organization, facilitating the accumulation of key molecular precursors to early biopolymers [3,4,29].

In this way, boron-mediated selection may have contributed to the emergence of biologically relevant molecules by linking environmental fluctuations to the persistence of specific chemical structures.

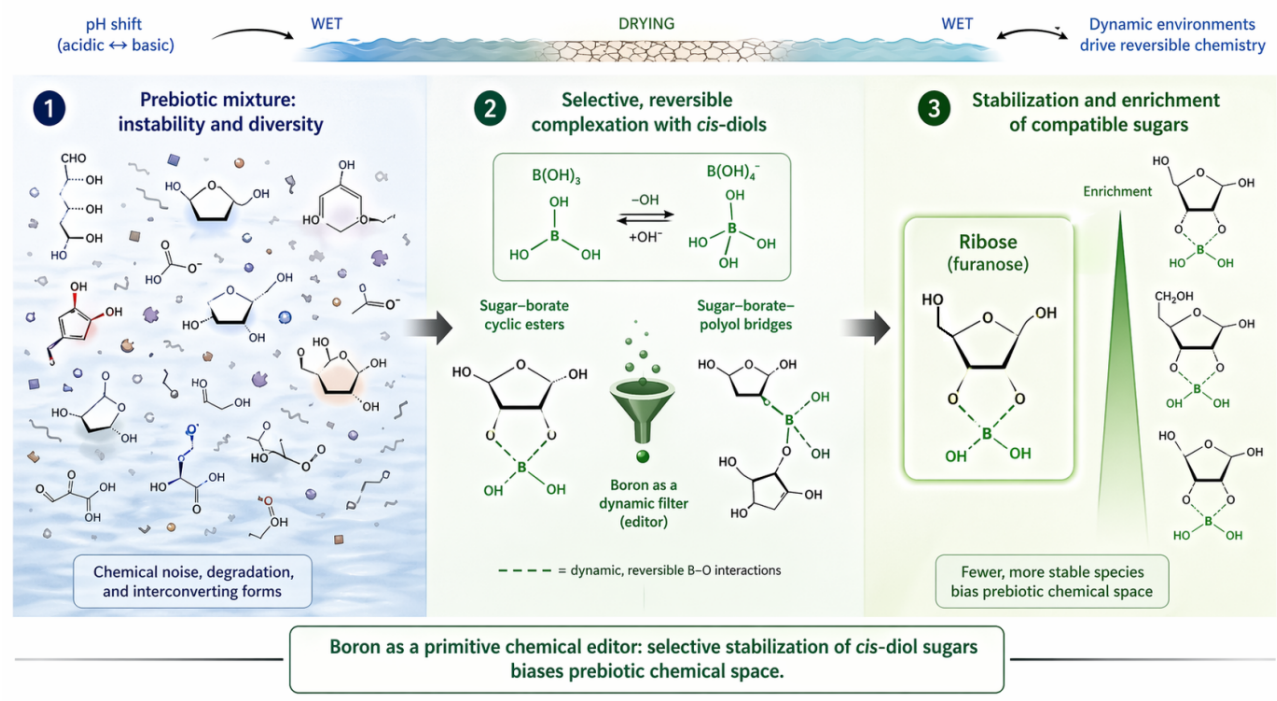

Figure 2. Boron-mediated selection of cis-diol sugars in prebiotic mixtures. In aqueous environments, boron exists as boric acid and borate, with speciation governed by pH (pKa ≈ 9.2). The tetrahedral borate species preferentially forms reversible cyclic esters with cis-diols, favoring geometrically compatible substrates such as furanose sugars. These interactions are moderately strong yet kinetically labile, enabling rapid exchange within complex mixtures. Borate can also generate crosslinked assemblies through bridging interactions between diol-containing molecules. Under fluctuating conditions (e.g., pH shifts, drying–wetting cycles), this dynamic covalent chemistry selectively stabilizes compatible structures while allowing less favorable species to dissociate. Such reversible complexation biases the composition of prebiotic chemical space toward enriched pools of cis-diol-containing sugars

6. Limitations, alternatives and open questions

Despite its conceptual appeal, the boron-mediated selection model raises several important uncertainties. The availability, concentration and spatial distribution of boron in specific prebiotic environments remain incompletely constrained, and competing ligands—such as phosphate, silicates or other polyols—may significantly influence boron–diol interactions [8,30–32]. In addition, while borate complexes are stabilizing under controlled conditions, their persistence and functional relevance under fluctuating, heterogeneous environments require further experimental validation [1,8,33–35].

Alternative selection mechanisms—including mineral surface interactions, eutectic freezing and phosphorylation chemistry—may operate in parallel with, or in competition with, boron-mediated processes. These mechanisms differ in their dependence on environmental parameters and in the types of selectivity they impose. A key challenge is therefore to determine whether boron acts as a dominant selector in specific niches or as one component within a broader network of interacting selection processes.

Future work should prioritize system-level investigations that move beyond simplified model reactions. Experiments that integrate multiple environmental variables—such as pH oscillations, drying–wetting cycles and mixed chemical systems—will be essential for evaluating how boron-mediated interactions function within realistic prebiotic contexts.

7. Outlook: dynamic selection as a general principle

The role of boron in prebiotic chemistry may exemplify a broader principle: reversible, environment-responsive interactions can act as selectors in complex chemical systems. Rather than directing specific reaction pathways, such processes bias molecular populations by stabilizing certain structures over others, thereby shaping chemical outcomes over time.

In this view, boron is not merely a stabilizing additive but part of a wider class of chemical agents capable of modulating molecular distributions through equilibrium bias and dynamic exchange. These mechanisms do not encode information in a biological sense, yet they impose constraints that guide the trajectory of chemical evolution.

Recognizing the role of such dynamic selection processes may be essential for understanding how prebiotic chemistry transitioned from disordered mixtures to systems capable of persistence, organization and, ultimately, function. More broadly, this perspective suggests that the emergence of biologically relevant molecules may have been driven not solely by synthetic pathways, but by physicochemical processes that selectively stabilized compatible structures within complex environments.

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Conflicts of Interest: The authors declare no competing interests.

References

[1] Dembitsky, V. M., Al Quntar, A. A. A., & Srebnik, M. (2011). Natural and synthetic small boron-containing molecules as potential inhibitors of bacterial and fungal quorum sensing. *Chemical Reviews*, *111*(1), 209-237.

[2] Dembitsky, V. M., Smoum, R., Al-Quntar, A. A., Ali, H. A., Pergament, I., & Srebnik, M. (2002). Natural occurrence of boron-containing compounds in plants, algae and microorganisms. *Plant Science*, *163*(5), 931-942.

[3] Dembitsky, V. M., Terent'ev, A. O., & Scorei, I. R. I. (2026). Borate-Bridged Protolipids: A Prebiotic Route to Abiotic Membranes. *Life*, *16*(5), 714.

[4] Dembitsky, V. M., Terent'ev, A. O., Baranin, S. V., & Scorei, R. I. (2026). Life with boron: Steroid architecture and the chemistry of marine boronosteroids. *Marine Drugs*, *24*(3), 113.

[5] Dembitsky, V. M., Terent'ev, A. O., Gursky, M. E., & Baranin, S. V. (2026). Fascinating and intriguing biomolecules: The chemistry of boron complexes with carbohydrates, glycolipids, and steroids. *Vietnam Journal of Chemistry*, *64*(2), 159-194.

[6] Dembitsky, V. M., Terent'ev, A. O., Stolbov, L. A., Pogodin, P. V., Filimonov, D. A., & Poroikov, V. V. (2025). Salicylic Acid and Its Boron Complexes as Quorum Sensing Molecules. *Molecular Pharmaceutics*, *22*(11), 6499-6509.

[7] Dembitsky, V. M., Terent'ev, A. O., Baranin, S. V., & Gursky, M. E. (2025). Aromatic compounds and their fascinating boron complexes as potential quorum sensing molecules. *Vietnam Journal of Chemistry*, *63*(6), 883-911.

[8] Dembitsky, V. M., Rosenberg, G. S., & Zanfera, V. M. (2023). *The Evolutionary Pathway to the Biomembrane. The Role of Low Molecular Weight Polyols in the Formation of the Protomembrane.* Editorial & Publ. Department IEVRB RAS, Russia.

[9] Sutton, S. M., Pulletikurti, S., Lin, H., Krishnamurthy, R., & Liotta, C. L. (2025). Abiotic aldol reactions of formaldehyde with ketoses and aldoses—Implications for the prebiotic synthesis of sugars by the formose reaction. *Chem, 11*(11), 102553.

[10] Briš, A., Baltussen, M. G., Tripodi, G. L., Huck, W. T., Franceschi, P., & Roithová, J. (2024). Direct analysis of complex reaction mixtures: formose reaction. *Angewandte Chemie, 136*(6), e202316621.

[11] Kopetzki, D., & Antonietti, M. (2011). Hydrothermal formose reaction. *New Journal of Chemistry, 35*(9), 1787-1794.

[12] Ono, C., Sunami, S., Ishii, Y., Kim, H. J., Kakegawa, T., Benner, S. A., & Furukawa, Y. (2024). Abiotic ribose synthesis under aqueous environments with various chemical conditions. *Astrobiology, 24*(5), 489-497.

[13] Takahashi, Y., Kim, H. J., Benner, S. A., Kakegawa, T., & Furukawa, Y. (2026). Ribose accumulation in borate-rich prebiotic environments. *Astrobiology, 26*(2), 99-107.

[14] Hipparagi, L., Umesh, R., & Harohally, N. V. (2025). Conversion of Cyclic Ribose to Acyclic Ribose under Prebiotic Conditions: Implications for Ribose Selection as the RNA Sugar. *ACS Earth and Space Chemistry, 9*(7), 1848-1857.

[15] Kurrle, N. J., Bechtel, M., Hampel, N., & Trapp, O. (2026). Prebiotic Investigations and Reaction Network Analysis on the Wöhler-RNA System. *ChemSystemsChem, 8*(2), e00046.

[16] Benner, S. A., Kim, H. J., & Carrigan, M. A. (2012). Asphalt, water, and the prebiotic synthesis of ribose, ribonucleosides, and RNA. *Accounts of Chemical Research, 45*(12), 2025-2034.

[17] Smith, E. M., Shirey, S. B., Richardson, S. H., Nestola, F., Bullock, E. S., Wang, J., & Wang, W. (2018). Blue boron-bearing diamonds from Earth's lower mantle. *Nature, 560*(7716), 84-87.

[18] Helvacı, C. (2017). Borate deposits: An overview and future forecast with regard to mineral deposits. *Journal of Boron, 2*(2), 59-70.

[19] Ricardo, A., Carrigan, M. A., Olcott, A. N., & Benner, S. A. (2004). Borate minerals stabilize ribose. *Science, 303*(5655), 196-196.

[20] Furukawa, Y., Horiuchi, M., & Kakegawa, T. (2013). Selective stabilization of ribose by borate. *Origins of Life and Evolution of Biospheres, 43*(4), 353-361.

[21] Scorei, I. R. (2025). Boron and the three evolutionary stages of life from chemical emergence to digital continuity. *Discover Life, 55*(1), 40.

[22] Benner, S. A. (2004). Understanding nucleic acids using synthetic chemistry. *Accounts of Chemical Research, 37*(10), 784-797.

[23] Junior, E. S. A., da Silva, J. N., Gato, A. D. S., Cresencio, L. G., & de Oliveira, K. M. T. (2025). Theoretical investigation of the reaction between pyrimidine nucleobases, D-ribose, and Phosphates in the prebiotic synthesis of RNA nucleosides and nucleotides. *Cuadernos de Educación y Desarrollo-QUALIS A4, 17*(7), e8986-e8986.

[24] Ali, H. A., Dembitsky, V. M., & Srebnik, M. (2005). *Contemporary Aspects of Boron: Chemistry and Biological Applications.* Studies in Inorganic Chemistry, ScienceDirect.

[25] Dembitsky, V. M., Terent'ev, A. O., & Baranin, S. V. (2026). Functional plasticity of microbial siderophores in iron-and boron-rich niches. *Applied Microbiology, 6*(4), 50.

[26] White, S. B., & Rimmer, P. B. (2024). Do-Nothing Prebiotic Chemistry: Chemical Kinetics as a Window into Prebiotic Plausibility. *Accounts of Chemical Research, 58*(1), 1-10.

[27] Nogal, N., Sanz-Sánchez, M., Vela-Gallego, S., Ruiz-Mirazo, K., & de la Escosura, A. (2023). The protometabolic nature of prebiotic chemistry. *Chemical Society Reviews, 52*(21), 7359-7388.

[28] Ruiz-Mirazo, K., Briones, C., & de la Escosura, A. (2014). Prebiotic systems chemistry: new perspectives for the origins of life. *Chemical Reviews, 114*(1), 285-366.

[29] Scorei, R. (2012). Is boron a prebiotic element? A mini-review of the essentiality of boron for the appearance of life on earth. *Origins of Life and Evolution of Biospheres, 42*(1), 3-17.

[30] Cleaves II, H. J. (2008). The prebiotic geochemistry of formaldehyde. *Precambrian Research, 164*(3-4), 111-118.

[31] Attwater, J., Wochner, A., Pinheiro, V. B., Coulson, A., & Holliger, P. (2010). Ice as a protocellular medium for RNA replication. *Nature Communications, 1*(1), 76.

[32] Benner, S. A. (2014). Paradoxes in the origin of life. *Origins of Life and Evolution of Biospheres, 44*(4), 339-343.

[33] Kitadai, N., & Maruyama, S. (2018). Origins of building blocks of life: a review. *Geosci Front 9*, 1117–1153.

[34] Sutherland, J. D. (2017). Opinion: Studies on the origin of life—the end of the beginning. *Nature Reviews Chemistry, 1*(2), 0012.

[35] Dembitsky, V. M., Terent'ev, A. O., & Baranin, S. V. (2026). Life with boron: Microbial boron-binding siderophores, adaptation, and function. *Microbiology Research, 17*(3), 57.