ChemSystemsChem

Concept
doi.org/10.1002/syst.202300002

Chemistry Europe
European Chemical Societies Publishing

www.chemsystemschem.org

Chemobrionics Database: Categorisation of Chemical Gardens According to the Nature of the Anion, Cation and Experimental Procedure**

Carlos Pimentel,*[a] Mingchuan Zheng,[b] Julyan H. E. Cartwright,[c, d] and C. Ignacio Sainz-Díaz[c]

Considering the growing importance of the field of chemobrionics since the term was coined in 2015 and the increase in the number of published papers, it has become necessary to catalogue all the papers published to date. Here, we present the chemobrionics database, which lists all the chemical gardens synthesised according to their anion, cation and experimental protocol. The aim of this database is to encourage the study and dissemination of chemical gardens in order to find new experimental avenues in the field of chemobrionics. As this is such a fruitful field, the database is continuously updated.

1. Introduction

Chemical gardens are self-organising structures that biomimic plant-like structures with tube and vesicle shapes. Johann Glauber described these structures for the first time in 1646.[1] Since then, chemical gardens have attracted the attention of scientists, who have recently called this research field chemobrionics.[2] Chemobrionics can be used to study a number of subjects among which are corrosion, sensors and electrochemistry, just to name a few.[2–5] Chemobrionics can help answer the most longstanding scientific question, i.e., how did life originate, given that life could have originated in oceanic hydrothermal vents, which are natural chemical gardens.[2,6–11]

Classical experiments on chemical gardens were performed by adding to a solution of an anion a metal salt (except the too-soluble alkali metals). The metal salt can be added in solid form, as single crystal or as a pellet of polycrystalline powder, or as a second liquid. The most common anion solution used to promote the growth of chemical gardens has been silicate, but many others have also been used.[2] In the case of metals, a large number of them have been used, e.g., Ca, Mg, Fe, Ba, Cu…[2] In addition to what the classical experiments describe, other kinds of experiments have been conducted to promote the growth of chemical gardens, e.g., using gel or paste,[12–14] by corrosion,[3,15] by performing electrochemical experiments[5] or carrying out experiments in confined geometries.[9,16–18]

Therefore, taking into account the wide number of conditions to promote the growth of chemical gardens, here we present the chemobrionics database, which curates all the papers published to date about chemical gardens, to the best of our knowledge. This database is intended to be a tool for all researchers in the field of chemobrionics, where they can search for all synthesised chemical gardens and to open up new avenues of research in the field of chemobrionics.[19,20]

2. Discussion

Since the term chemobrionics was coined in 2015, the number of publications in this field has increased. From the first description of chemical gardens by Glauber[1] in the 17th century up to and including 2015, 95 papers were published. Since then and up to the end of 2022, when this article was written, 104 papers have been published (Figure 1).‡ In addition, 2 papers have been already accepted and taken into account in the database (although they are not shown in Figure 1).[21,22] This increase in the number of publications demonstrates the growing scientific interest in this field, as also testified by the award of a COST project of the European Union (COST Action CA17120 Chemobrionics).

Therefore, and in order to help the scientific community, the chemobrionics database has been designed. This database can be downloaded from the zenodo repository as a .csv file[19] or can be consulted live on a dedicated website (Figure 2).[20] In this database, the chemical gardens have been catalogued according to the anion and cation used, and the experimental

---

[a] C. Pimentel
Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, < Univ. Gustave Eiffel, ISTerre, 38000 Grenoble, France
E-mail: carlos.pimentel-guerra@univ-grenoble-alpes.fr
Homepage: https://cpimentelguerra.com
[b] M. Zheng
Department of Chemical Engineering and Biotechnology, West Cambridge Site, University of Cambridge, Philippa Fawcett Drive, Cambridge CB3 0AS, UK
[c] J. H. E. Cartwright, C. I. Sainz-Díaz
Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada, 18100 Armilla, Granada, Spain
[d] J. H. E. Cartwright
Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, 18071 Granada, Spain

[**] *The chemobrionics database is available at 10.5281/zenodo.6607124 and also as a live version at https://cpimentelguerra.com/chemobrionics/.*

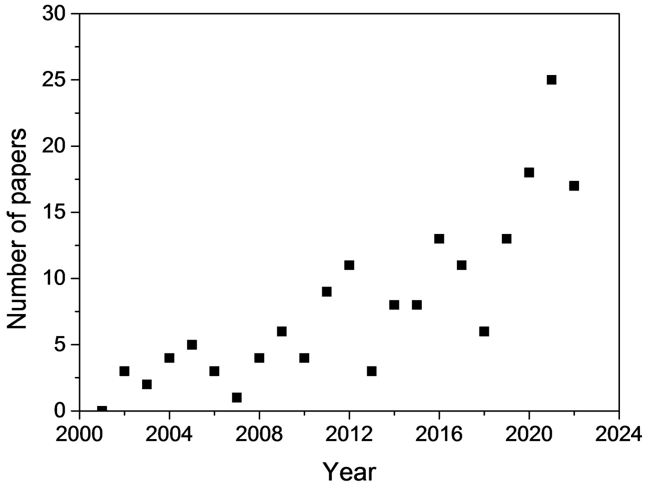


Figure 1. Number of papers (and books) published per year since 2000. Before 2000 only 23 works were published. The two accepted papers that will be published in 2023 are not included in the graph but are included in the database.

setup. Accompanying this information are the references to the papers describing these chemical gardens. Therefore, in this database, a chemical garden with the same anion and cation may appear in several entries if different experimental methods have been used to synthesise it or if it has been combined with an additional ion. For example, the combination of silicate with calcium appears a total of 8 times in the database, as it has been synthesised using three different experimental approaches (solid, gel and paste), but it has also been synthesised by combining them with CO_2, with carbonate anion, with phosphate anion and with iron cation. These calcium silicate gardens have been described in a total of 27 different papers.

Thanks to this database, some interesting results can be extracted on the main chemical gardens on which chemobrionics research has focused. The main anion used has been silicate (53 entries in the database), followed by carbonate (35 entries) and phosphate (25 entries). In Figure 3A can be seen all those anions which have more than 5 entries in the database. Among the cations (Figure 3B), Ca^{2+} has been the most used cation (31 entries), followed by Cu^{2+} (21 entries) and Fe^{2+} (20 entries). Focusing on the methods used, using one solid phase (i.e., solid setup in the database) and mixing two liquid phases (i.e., liquid setup) have been by far the most used methods, appearing in 86 and 72 entries, respectively.

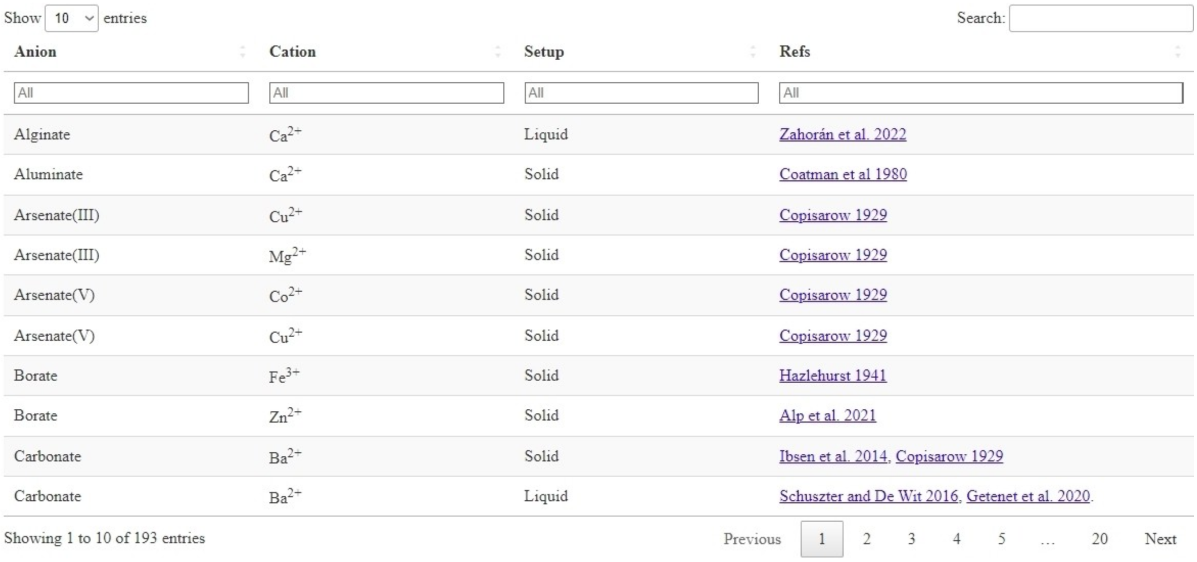
In other cases, anions and cations only appear in one entry, so that these routes of synthesis of chemical gardens are open to new experimental contributions. For instance, that is the case of aluminate,[23] chlorite[24] or tungstate,[25] for anions; and lithium,[17,26] cerium[27] or gold,[1,28] for cations.

Within the database, there are chemical gardens that can be considered special, because they cannot be differentiated by anions and cations, so the same terms appear in both fields of the database, such as ice,[29] steel,[3,15] Portland cement,[30] and xenon hydrates.[31]

It is also interesting to note that some researchers have studied natural structures that they have described as chemical gardens, although such structures are less accessible than the experimental synthesis of chemical gardens and, therefore, there are fewer references. The natural structures were composed of carbonates,[8,32] oxides,[6,33] sulfates,[34] or methane hydrates.[35]

3. Summary and Outlook

In summary, given the increasing number of works in the field of chemobrionics, we have found it helpful to create a database



Anion	Cation	Setup	Refs
All	All	All	All
Alginate	Ca^{2+}	Liquid	Zahorán et al. 2022
Aluminate	Ca^{2+}	Solid	Coatman et al 1980
Arsenate(III)	Cu^{2+}	Solid	Copisarow 1929
Arsenate(III)	Mg^{2+}	Solid	Copisarow 1929
Arsenate(V)	Co^{2+}	Solid	Copisarow 1929
Arsenate(V)	Cu^{2+}	Solid	Copisarow 1929
Borate	Fe^{3+}	Solid	Hazlehurst 1941
Borate	Zn^{2+}	Solid	Alp et al. 2021
Carbonate	Ba^{2+}	Solid	Ibsen et al. 2014, Copisarow 1929
Carbonate	Ba^{2+}	Liquid	Schuszter and De Wit 2016, Getenet et al. 2020.

Showing 1 to 10 of 193 entries

Figure 2. Screenshot of the chemobrionics database (accessed 16/12/2022).[20] The database is organized in 4 columns: anion, cation, setup and references (refs). In each column there is a search field to search within the column. At the top right, there is a search field to browse the entire database.

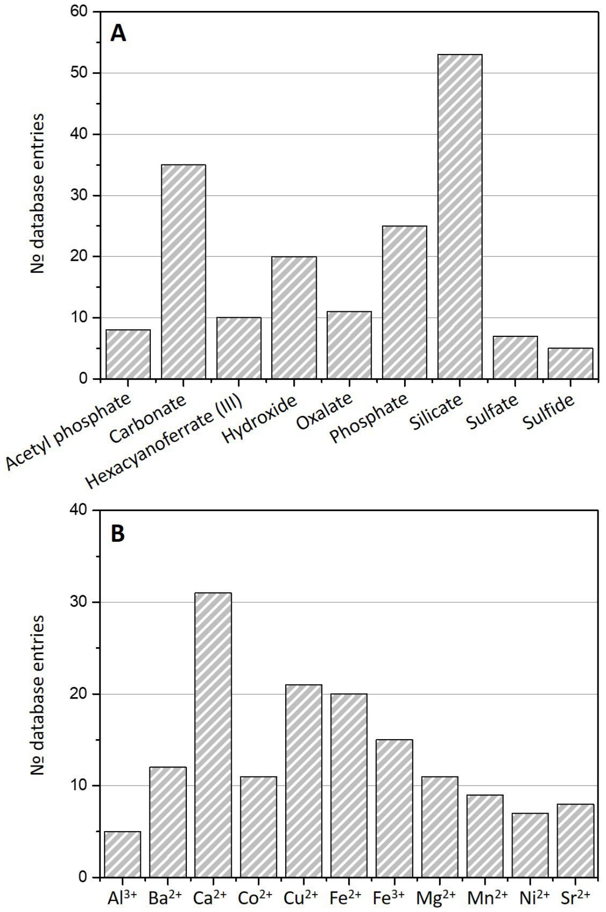


Figure 3. Number of database entries per anion (A) and cation (B), considering all the ions with more than 5 entries in the database.

to collect and catalogue them in order to facilitate the bibliographic work of future research. In addition, this database can be used to detect research gaps on which to focus future works. This database is live and the references cited in it are periodically updated. For this reason, the zenodo repository is used for its distribution, where future updates can be easily found. Future updates of the database can be adapted to the needs of the community by making it more specific as necessary.

Supporting Information

A csv file with the complete database can be found at 10.5281/zenodo.6607124.

Acknowledgements

The authors would like to acknowledge the contribution of the European COST Action CA17120 supported by the EU Framework Programme Horizon 2020. CP has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101021894 [CARS-CO2]. The authors would also like to thank the researchers who sent their papers for inclusion in the database.

Conflict of Interest

There are no conflicts to declare.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at DOI: 10.5281/zenodo.6607124, reference number 6607124.

Keywords: Chemical Gardens · Chemobrionics · Inorganic Chemistry

[1] J. R. Glauber, *Furni novi philosophici, sive Descriptio artis distillatoriæ novæ; nec non spirituum, olcorum, florum, aliorumque medicamentorum illus beneficio, facilimâ quâdam & perculiari viá è vegetabilibus, animalibus & mineralibus conficiendorum & quidem magno cum lucro; agens quoque de illorum usu tàm chymico quàm medico, edita & publicata in gratiam veritatis studiosorum*, Prostant Apud J. Janssonium, Amsterodami, **1651**.

[2] L. M. Barge, S. S. S. Cardoso, J. H. E. Cartwright, G. J. T. Cooper, L. Cronin, A. De Wit, I. J. Doloboff, B. Escribano, R. E. Goldstein, F. Haudin, D. E. H. Jones, A. L. Mackay, J. Maselko, J. J. Pagano, J. Pantaleone, M. J. Russell, C. I. Sainz-Díaz, O. Steinbock, D. A. Stone, Y. Tanimoto, N. L. Thomas, *Chem. Rev.* **2015**, *115*, 8652–8703.

[3] F. Brau, F. Haudin, S. Thouvenel-Romans, A. D. Wit, O. Steinbock, S. S. S. Cardoso, J. H. E. Cartwright, *Phys. Chem. Chem. Phys.* **2018**, *20*, 784–793.

[4] E. Escamilla-Roa, J. H. E. Cartwright, C. I. Sainz-Díaz, *ChemSystemsChem* **2019**, *1*, e1900011.

[5] D. Spanoudaki, E. Pavlidou, D. Sazou, *ChemSystemsChem* **2021**, *3*, e2000054.

[6] L. M. Barge, S. S. S. Cardoso, J. H. E. Cartwright, I. J. Doloboff, E. Flores, E. Macías-Sánchez, C. I. Sainz-Díaz, P. Sobrón, *Proc. R. Soc. A* **2016**, *472*, 20160466.

[7] L. M. Barge, E. Branscomb, J. R. Brucato, S. S. S. Cardoso, J. H. E. Cartwright, S. O. Danielache, D. Galante, T. P. Kee, Y. Miguel, S. Mojzsis, K. J. Robinson, M. J. Russell, E. Simoncini, P. Sobron, *Orig Life Evol Biosph* **2017**, *47*, 39–56.

[8] S. S. S. Cardoso, J. H. E. Cartwright, A. G. Checa, C. I. Sainz-Díaz, *Acta Biomater.* **2016**, *43*, 338–347.

[9] Y. Ding, B. Batista, O. Steinbock, J. H. E. Cartwright, S. S. S. Cardoso, *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 9182–9186.

[10] C. I. Sainz-Díaz, E. Escamilla-Roa, J. H. E. Cartwright, *Geochem. Geophys. Geosyst.* **2018**, *19*, 2813–2822.

[11] E. Kotopoulou, M. Lopez-Haro, J. J. Calvino Gamez, J. M. García-Ruiz, *Angew. Chem. Int. Ed.* **2021**, *60*, 1396–1402; *Angew. Chem.* **2021**, *133*, 1416–1422.

[12] H. Birkedal, Y. Chen, in *Advances in Inorganic Chemistry* (Eds.: D. Ruiz-Molina, R. van Eldik), Academic Press, **2020**, pp. 269–298.

[13] B. C. Batista, O. Steinbock, *Chem. Commun.* **2022**, *58*, 12736–12739.

[14] D. E. H. Jones, U. Walter, *J. Colloid Interface Sci.* **1998**, *203*, 286–293.

[15] F. Brau, S. Thouvenel-Romans, O. Steinbock, S. S. S. Cardoso, J. H. E. Cartwright, *Soft Matter* **2019**, *15*, 803–812.

[16] Q. Wang, F. M. Zanotto, O. Steinbock, *J. Phys. Chem. C* **2020**, *124*, 21617–21624.

[17] M. Emmanuel, D. Horváth, Á. Tóth, *CrystEngComm* **2020**, *22*, 4887–4893.

[18] L. A. M. Rocha, L. Thorne, J. J. Wong, J. H. E. Cartwright, S. S. S. Cardoso, *Langmuir* **2022**, *38*, 6700–6710.

[19] C. Pimentel, M. Zheng, C. I. Sainz-Díaz, J. H. E. Cartwright, **2022**, 10.5281/zenodo.6607124.

[20] C. Pimentel, M. Zheng, C. I. Sainz-Díaz, J. H. E. Cartwright, "Chemobrionics Database Webpage," can be found under https://cpimentelguerra.com/chemicalgardens/, **2022**. (Accessed 16/12/2022).
[21] S. Huld, S. McMahon, S. Sjöberg, P. Huang, A. Neubeck, *Astrobiology* **2023**, *23*, 24–32.
[22] V. K. Patel, B. Busupalli, *Chem. Commun.* **2023**, *59*, 768–771.
[23] R. D. Coatman, N. L. Thomas, D. D. Double, *J. Mater. Sci.* **1980**, *15*, 2017–2026.
[24] V. V. Udovichenko, P. E. Strizhak, A. Toth, D. Horwath, S. Ning, J. Maselko, *J. Phys. Chem. A* **2008**, *112*, 4584–4592.
[25] C. Pimentel, J. H. E. Cartwright, C. I. Sainz-Díaz, *ChemSystemsChem* **2020**, *2*, e2000023.
[26] M. Emmanuel, E. Lantos, D. Horváth, Á. Tóth, *Soft Matter* **2022**, *18*, 1731–1736.
[27] W. J. Clunies Ross, *J. Proc. R. Soc. N. S. W.* **1910**, *44*, 583–592.
[28] G. D. Zissi, G. Angelis, G. Pampalakis, *ChemSystemsChem* **2021**, *3*, e2000018.
[29] J. H. E. Cartwright, B. Escribano, D. L. González, C. I. Sainz-Díaz, I. Tuval, *Langmuir* **2013**, *29*, 7655–7660.
[30] S. S. S. Cardoso, J. H. E. Cartwright, O. Steinbock, D. A. Stone, N. L. Thomas, *Struct. Chem.* **2017**, *28*, 33–37.
[31] X. Fu, J. Jimenez-Martinez, T. P. Nguyen, J. W. Carey, H. Viswanathan, L. Cueto-Felgueroso, R. Juanes, *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 31660–31664.
[32] L. A. M. Rocha, C. Gutiérrez-Ariza, C. Pimentel, I. Sánchez-Almazo, C. I. Sainz-Díaz, S. S. S. Cardoso, J. H. E. Cartwright, *Geochem. Geophys. Geosyst.* **2021**, *22*, e2021GC009724.
[33] L. M. Silva-Bedoya, E. Watkin, L. L. Machuca, *Mater. Corros.* **2021**, *72*, 1138–1151.
[34] J. You, Y. Liu, D. Zhou, Y. Yang, *Sci. Rep.* **2021**, *11*, 22712.
[35] X. Fu, W. F. Waite, C. D. Ruppel, *J. Geophys. Res. [Oceans]* **2021**, *126*, e2021JC017363.

Manuscript received: January 9, 2023
Accepted manuscript online: February 15, 2023
Version of record online: March 8, 2023