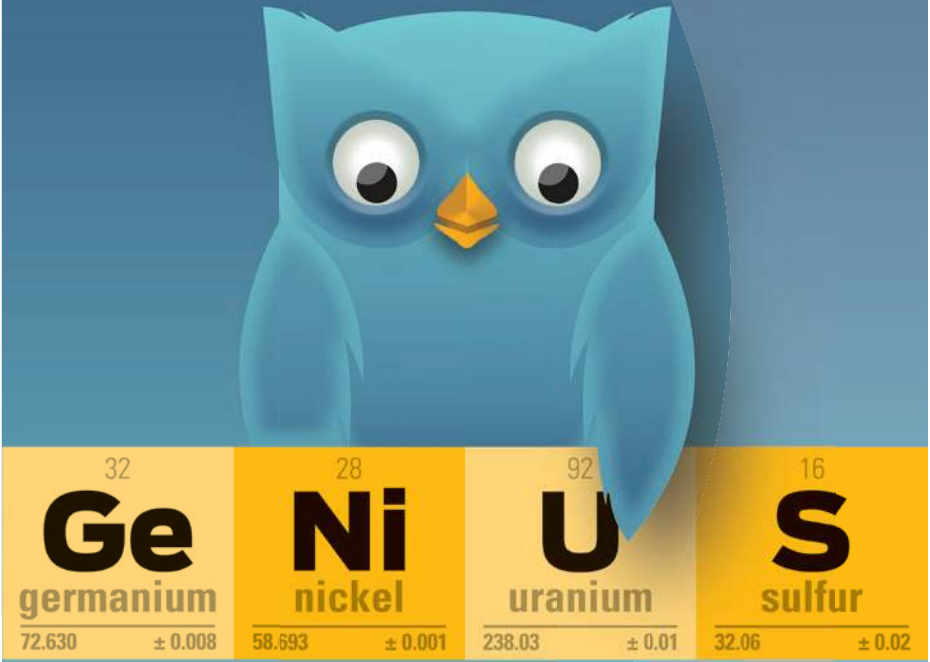
SUSTAINABLE CHEMISTRY NoteBook

2

The Element's Guardians: The Periodic Table for Green and Sustainable Chemistry



2026

Chimie ParisTech | PSL

VEOLIA

SUSTAINABLE CHEMISTRY 2

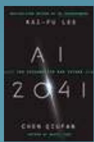
NoteBook

The Element's Guardians: The Periodic Table for Green and Sustainable Chemistry

“The Periodic Table is not just a map of elements; it is a story still being written—and in this volume, every element holds a lesson from the past and a promise for tomorrow, to be understood by those brave enough to ask: how can we use this knowledge to protect rather than pollute?”

陈楸帆 **Stanley Qiufan CHEN**

Author of ***Waste Tide*** & ***AI2041***,
Research Scholar at Yale Univ., Berggruen Fellow,
Asia21 Next Gen Fellow



SUSTAINABLE CHEMISTRY NoteBook 2

Summary

Creative and ethical,
and at its best,
beautiful

Forewords

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Everything we touch, breathe, and use is chemistry.

In the first volume of *The Sustainable Chemistry Notebook*, students from Chimie Paris and Chimie Pékin explored how the principles of Green and Sustainable Chemistry can reshape our relationship with materials, reactions, and resources. With the guidance of educators, researchers, and the enduring support of John Warner, this collaborative journey now continues with a deeper look at one of the greatest scientific frameworks ever conceived: **the Periodic Table of Elements**.

When Dmitri Mendeleev first arranged the elements more than 150 years ago, he revealed an underlying order in matter, a structure that reflected what was known and predicted what was yet to be discovered. The table appears complete, and yet our understanding continues to evolve.

The Periodic Table is often taught as something to memorize, but it is far more than that. When approached only as memorization, it can feel like a chore and push students away. But when approached as a way of seeing **infinite patterns and possibilities**, it invites curiosity and opens the door to the wonders of science.

Each element carries a story in potential, waiting to coalesce not only into new materials, medicines, and technologies, but also into **new ways of living, learning, and relating to one another and the world around us**.

The Periodic Table is one of the few languages on Earth that is truly **shared**. A chemist in Beijing, Dubai, Paris, San Francisco, Istanbul, Nairobi, São Paulo, Tokyo, Marrakech or Mumbai reads the same symbols and sees the same **horizon of possibility**—yet brings a unique perspective shaped by culture, community, and experience. In this way, the table allows individuals to think and create **together**, across borders, disciplines, and generations.

It helps us ask: *What is possible here? What should be created? And for a sustainable future, what must be avoided?* It teaches us that chemistry is not only what we can make, but what we choose to make. The work of chemistry is therefore never only technical. It is **creative and ethical, and at its best, beautiful**.

In the 21st century, chemistry stands at the crossroads of disciplines. Physics, biology, mathematics, data science, and materials science now converge to shape how we design molecules and sustainable solutions.

This second volume, *Elemental Guardians*, is an invitation to rediscover the elements—not as static facts, but as **living connections** between matter, history, science, society, and sustainability. It celebrates dialogue and shared learning, bringing together historical knowledge, contemporary research, and the imagination of future chemists.

The students of Chimie ParisTech – PSL, together with their peers from Chimie Pékin, are at the center of this shared work. Guided by faculty, researchers, and practitioners across generations, they remind us that the most important progress begins in **curiosity, listening, and collaboration**. They may not have all the answers—no generation ever does—but they are already shaping the questions that will define the future of chemistry. The future of chemistry is being co-created—today, together—with education as the key to understanding and applying the fundamentals of a chemistry that sustains life.

This generation of chemists is not only using the Periodic Table, they are **reinterpreting it**.

Acknowledgements, Purpose & Contributors

**First and foremost,
we would like to say thank you.**

Thank you to all those who contributed to this volume, not only for their time and expertise, but above all for their intellectual honesty and courage. Each contributor accepted a fundamental premise: **we all look at the world through a distorted lens**, shaped by where we stand, our backgrounds, our disciplines, our constraints, and our responsibilities. Acknowledging this bias is not a weakness: It is the starting point for meaningful dialogue and better collective choices.

The *Sustainable Chemistry Notebook* series was created to make space for this kind of dialogue **to understand the Chemistry**. Today, we talk extensively about ecology, climate change, digitalization, geopolitics, industrial transformation, security, new economics or the growing role of artificial intelligence, and Quantum. We identify problems, promote actions, build partnerships, and multiply initiatives. But a critical question often remains in the background: **are we framing the issues correctly, and are we making truly informed and relevant choices?**
With this project, we deliberately chose to work on what we believe to be the most powerful and fundamental lever for prevention, adaptation, resilience, transition, and transformation, whatever name we give to these processes: **Education and Transmission**.

Education here is understood in its broadest sense: the ability to share knowledge, to listen to one another, to confront perspectives, to question certainties, and to collectively build understanding. This work was deliberately conducted as a **transgenerational and ego-free process**, independent of titles or degrees, where experience, curiosity, and questioning mattered more than formal credentials, and where **every voice was and remains equally important**. One simple rule guided this work: openness through **sharing**, **listening**, **and mutual respect**, **and modesty**.

For this commitment, this openness, and this collective intelligence, **bravo and a heartfelt thank you to all**.

With Volume 2 (2025), the *Sustainable Chemistry Notebook* continues its journey by returning to the foundations of matter: **the periodic table**. Each element is a building block, each bond a link, forming a structure that supports a **Right and Sustainable Chemistry**, grounded in knowledge, care, responsibility, and long-term vision.

Acknowledgements, Purpose & Contributors

Building on the work initiated in Volume 1, students from **Chimie ParisTech**, **Chimie Pékin** and experts from **industries, academic institutions, and other partner organizations** continued their exchanges in a **transgenerational**, **ego-free process**, where every voice was equally important. They shared experiences, lessons learned, and perspectives for the future, explored how the 12 Principles of Chemistry can be implemented and strengthened, and identified priorities for action in an increasingly complex and interconnected world.

This work was guided by a simple principle: **openness through sharing**, **listening**, **and mutual respect**, combining fundamental chemistry, insights from the periodic table, real-world challenges, and forward-looking thinking to build a collective vision for sustainable practice.

MERCI

*A heartfelt and huge thank you to the students of **Beijing University of Chemical Technology (BUCT)** and **Chimie ParisTech PSL** for their trust and dedication. BRAVO for the outstanding quality of your work!*

*The content of this volume was consolidated, reviewed, structured, and translated by the student Colibri Team 2025: **James Robin-Weir, Léo Gérard, Baptiste Vesselle, Pauline Séguron, Lucie Girard, Leonnie Bouvet, and Alexandre Derouet**, with the support of **Fabrice Gayot (Quarante Six)**. The workshops were facilitated by **Sonia Graja, Christophe Zobrist, and Aurore Eon-Fayoux**. The project was coordinated by the **Colibri Team** and* **Ismahane El Bahloul-Remonnay***, Head of Anticipation and Alliances, and Coordinator of the **Veolia Chemical Transition program** (2020-2026).*

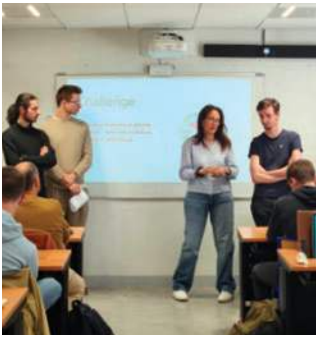
What you see here is only the quintessential of their full work and the valuable contributions of many others, if anyone is interested in exploring it further, feel free to reach out.

*Education, Prevention, and Science know no boundaries and no expiration date. No generations, no frontiers, only shared curiosity and an unwavering passion for discovery and **#Chemistry.***

Projet Colibri

QUARANTE·SIX
Imprimez. Exprimez.

FORESIGHT WORKSHOP PARIS & BEIJING




2025
Chimie Chinoise :
Sagesse Avant Mendeleïev


Travaux existants


02
Alchimie taoïste
Quête d'immortalité et élixir de vie


Matériaux ava


Introduction

Students from Chimie ParisTech & Chimie Pékin revisited, questioned, and enriched the principles developed in Volume 1: James Robin-Weir, Leo Gerard, Baptiste Vesselle, Pauline Seguron, Leonnie Bouvet, Lucie Girard, Alexandre Derouet, Apolline Pierlot, Ilan LLug, Victor Dodin, Lucas Berell, Jeremie Chrétien, Quentin Bravo, Maxime Eichelbrenner, Grégoire Meyer, Bastien Faurie, Lucien Bouyssou, Romane Sillon, Gaetan Massin, Pénélope Goirand, Léanne Bourasseau, Orphée Guironnet, Laure Ravet, Basile Gava, Camélia Azouaghe, Fanny Martinet, Camille Devinoy, Jeanne Tibourcio de la Corre, Eve Le Roy, Eleonore Loiseau, 张业梓 ZhangYeZi, 黄禹超 HuangYuChao, 王浩轩 WangHaoXuan, 张一超 ZhangYiChao, 刘雅心LiuYaXin, 陶宇鑫 TaoYuXin, 耿好 GengHao, 常羽鹲 ChangYuMeng, 刘震 LiuZhen, 任菲扬 RenFeiYang, 贾珅 JiaShen, 徐梓宸 XuZiChen, 毛奕涵 MaoYiHan, 闫悦琪 YanYueQi, 刘珂瑜 LiuKeYu, 余文博 YuWenBo, 王思睿 WangSiRui, 孙梦禹 SunMengYu, 陈楚文 ChenChuWen, 宋诺霏 SongNuoFei, 蔡文锴 CaiWenKai, 周坤杰 ZhouKunJie, 刘立 LiuLi, 刘冰睫 LiuBingJie, 冉舜天 RanShunTian,李妍 LiYan, 杜家润 DuJiaRun, 郑筱萸 ZhengXiaoYu, 胡晔 HuYe, 黄星宇 HuangXingYu, 程宪辉 ChengXianHui, 杨意旭 YangYiXu, 曾祥耘 Zeng Xiangyun, 李献喆 Li Xianzhe, 刘朴涵 Liu Puhan, 乔禹涵 Qiao Yuhan, 王雨涵 Wang Yuhan, 杨硕 Yang Shuo, 黄子 Huang Zixuan, 缪森辉 Miu Senhui, 王诗雅 Wang Shiya, 徐丽皓 Xu Lihao, 周铜 Zhou Tong, 董皓月 Dong Haoyue, 李晓芹 Li Xiaoqin, 孙佳慧Sun Jiahui, 徐晴萱 XuQingxuan, 詹子轩 Zhan Zixuan, 李耘成 Li Yuncheng, 刘凤宸 Liu Fengchen, 马伟泽 Ma Weize, 苏子翔 Su Zixiang, 孙洋 Sun Yang, 常铭钰 Chang Mingyu, 李钧善 Li Junshan, 刘硕 Liu Shuo, 肖磊 Xiao Lei, 郑世泽 Zheng Shize, 何易霖 He Yilin, 李基纶 Li Jilun, 李靓靓Li Liangliang, 张芷瑄 Zhang Zhixuan, 赵宏斌 Zhao Hongbin, 刘钰洋 Liu Yuyang, 马克 Ma Ke, 田佳颖 Tian Jiaying, 王之 Wang Zhi, 张瑀凌 Zhang Yuling.

They were supported throughout this process by **Anouk Galtayries**, **Marianne Ighilahriz**, **Christophe Thomas** & **Philippe Vernazobres** for their academic, and methodological guidance, and by the invaluable mentoring of contributors whose names and inspiring verbatim excerpts are woven throughout this document: **Guillermo Restrepo**, **Eeva Leinala**, **Youssef Habibi**, **Melissa Owen**, **Lyderic Bocquet**.

Experts and contributors from a wide diversity of organizations—including academic institutions, and other partner entities representing a broad range of métiers and geographical areas, actively contributed their operational experience, scientific expertise, and strategic vision: ***Sophie Achigar, Doan Bich-thuy, Christine Vicens, Clémence Conquet, Cyrine Slim, Domitille Giaume, Elodie Moreau-Guigon, Hasna Zerrouk-Billon, Jade Breton, Jean-François Soule, Jennifer Dallanese, Jérôme Raphanaud, Julien Hitce, Marie-Caroline Paris, Michel Minier, Odile Majerus, Olivier Teillac, Salohy Ratovona, Sarah Hercule-Bobroff, Sophie Griveau, Sophie Lebouil, Stéphanie Monjon, Vincent Semetey, Vincent Touraille, Virginie Vidal, Benjamin Chan-Piu, Caroline Geoffrois, Catherine Chevauche, Florence Poty, Jérôme Denis, Judith Martin, Loïc Berne, Marie-Thérèse Laguerre, Michel Cunnac, Mouloud Hendou, Nuno Marques Peirico, Sophie Petibon, Valérie Ingrand, Vincent Boisdon, Xavier Chaucherie, Sylvie Bourdon, Louis Reneteau, Claire Montet, Thomas Jouen, Mathilde Chachignon, Pascal Eloy, Yi Lu, Xiaohua Chen, Catherine Xia, Crystal ZHANG***.

Their combined contributions—rooted in industry, academia, and applied research—significantly enriched the collective reflection. We also warmly thank all the students who contributed to Volume 1, as well as everyone whose ideas and engagement have inspired and nourished this second volume.

Previously...

SUSTAINABLE CHEMISTRY NoteBook 1

The 12 Principles That Shaped Tomorrow

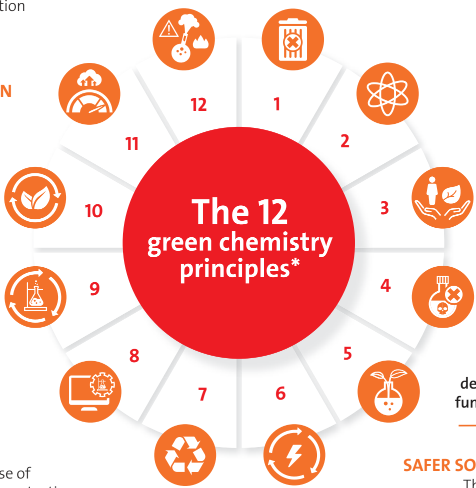
Education is the first foundation, flexible yet strong, like a reed bending without breaking.

With Volume 1 in 2024, the Sustainable Chemistry Notebook returned to the source: **the 12 Principles of Green Chemistry, envisioned by John Warner and Paul Anastas**, and re-interpreted by students and future chemists from Chimie ParisTech and Chimie Pékin, guided by Veolia's industrial experience and a collective of teams and partners engaged in the Chemical Transition. This first volume planted the seeds of a shared, transgenerational journey—**rooted in fundamentals, transmission, and responsibility**—and opened a first space for dialogue between cultures, educational traditions, and scientific perspectives across geographies.

With Volume 2 in 2025, the journey continues by exploring the very fabric of matter. **Just as a house cannot be built without tools to shape its foundations, the periodic table becomes the first instrument for constructing this house**: a guide for students discovering chemistry, and a lens for experienced chemists to rethink and reconnect with the discipline. Each element is a brick, each bond a beam, forming a structure that supports a Right and Sustainable Chemistry —a home grounded in knowledge, care, and responsibility.

The 12 Principles That Shaped Tomorrow

The 12 principles of green chemistry, the keystone of the ecological transformation



12 INHERENTLY SAFER CHEMISTRY FOR ACCIDENT PREVENTION

Substances and the form of a substance used in a chemical process **should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.**

11 REAL-TIME ANALYSIS FOR POLLUTION PREVENTION

Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

10 DESIGN FOR DEGRADATION

Chemical products should be designed so that at the end of their function **they break down into innocuous degradation products and do not persist in the environment.**

9 CATALYSIS

Catalytic reagents (as selective as possible) **are superior to stoichiometric reagents.**

8 REDUCE DERIVATIVES

Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) **should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.**

7 USE OF RENEWABLE FEEDSTOCKS

A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

PREVENTION 1

It is better to prevent waste than to treat or clean up waste after it has been created.

ATOM ECONOMY 2

Synthetic methods should be designed to maximize incorporation of all materials used in the process into the final product.

LESS HAZARDOUS CHEMICAL SYNTHESES 3

Wherever practicable, synthetic methods should be designed **to use and generate substances that possess little or no toxicity to human health and the environment.**

DESIGNING SAFER CHEMICALS 4

Chemical products **should be designed to preserve efficacy of function while reducing toxicity.**

SAFER SOLVENTS AND AUXILIARIES 5

The use of auxiliary substances (e.g., solvents, separation agents, etc.) **should be made unnecessary wherever possible and, innocuous when used.**

DESIGN FOR ENERGY EFFICIENCY 6

Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.

*** Paul T. Anastas and John Warner,** cofounders of the twelve principles.*

Forewords of the Future Chemists & Experts

Colibri Chemists Students
Chimie ParisTech Paris** & **Chimie Pékin

Why This Project? The Elemental Challenge: The Periodic Table in the Age of Sustainability.

Chemistry is at the heart of today's sustainable environmental transition and industrial transformation. The twelve principles of green chemistry discussed in the previous volume demonstrate a willingness and awareness to these issues. Although the development of concrete solutions to these challenges is costly, time-consuming and difficult, it is a global effort that needs to be made. The Chemical Sciences are essential to the sustainable transition. One of the most fundamental tools used by chemists since its creation and development is the periodic table of elements. It is often attributed to the Dmitri Mendeleev, who created it.

However, the collective scientific process that led to its creation is all too often forgotten, as is its evolution after Mendeleev. Taking inspiration from the past is always a step into the future. This is why it is necessary to look at the history of the periodic table, so that we can pit it against the challenges of today, which are different from the challenges of the past.

It is not the periodic organisation of the chemical properties of the elements highlighted by the periodic table that will be confronted, since this aspect of the table is its heart and essence. However, we can adapt it, questioning the use of certain elements, and shedding light on the issue of green chemistry transition.

Colibri Team: James Robin-Weir, Leo Gerard, Baptiste Vesselle, Pauline Seguron, Lucie Girard, Alexandre Derouet, Leonnie Bouvet.

The Youth Chemist perspective provides a looking glass to the different actors of the chemical story and can inspire the intergenerational future, for all geography.

*“Science is not
a man’s game,
it is a human game”*

Gitanjali Rao

1

The Periodic Table: A Chemical Epic Through the Ages

"The periodic table systematically classifies all chemical elements by atomic number, based on their electronic configuration and properties. An essential tool for chemists since 1869, it has undergone numerous evolutions and will continue to do so, particularly to integrate environmental and strategic parameters. Like a philatelist perfecting his collection, chemists rely on the historical properties of elements while leaving future generations the task of further evolving this universal reference."

Dr Anouk Galtayries
Dean of ***Chimie Pékin***
@BUCT (RP China)
& Associate Professor
@***Chimie ParisTech***-PSL (France)

"As a chemist and an educator of future chemists, I am deeply convinced that green chemistry is essential for building a sustainable future, by rethinking our processes to reduce their environmental impact from the very outset. Returning to fundamentals such as the periodic table of elements and revisiting it from this perspective opens up new perspectives, fosters the development of innovative thinking tools, and breaks away from rigid methodological approaches. Our primary mission is therefore to train young scientists, cultivating their creativity and their ability to innovate outside the box."

Mariane IGHILAHRIZ
Manager of industrial relations
and sustainable development
@***Chimie ParisTech***-PSL (France)

1.1 A Brief History of the Periodic Table

The History of the Periodic Table: Major Milestones

ANCIENT FOUNDATIONS — 700 · 800 · 900 · 1000 · 1100 · 1200 · 1300 · 1400 · 1500 · 1600

ANCIENT GREECE

Empedocles
(490-430 BC)
Four Elements (Earth, Water, Air, Fire)

Democritus
(460-370 BC)
Atomic Theory

Aristotle
(384-322 BC)
Fifth Element (Aether)

CHINA

Zou Yan
(305-240 BC)
Five Elements Theory (Wood, Fire, Earth, Metal, Water)

Wu Xing
Basis of Chinese
Natural Philosophy

ARAB WORLD

Jabir ibn Hayyan / Geber
(721-815)
Father of Chemistry

Al-Razi / Rhazes
(854-925)
Classification of Substances

Avicenna / Ibn Sina
(980-1037)
Elements and Minerals

ALCHEMISTS

Paracelsus
(1493-1541)
Tria Prima (Salt, Sulfur, Mercury)

Robert Boyle
(1627-1691)
The Sceptical Chymist (1661)
Modern Concept of Element

Georg Ernst Stahl
(1659-1734)
Phlogiston Theory

LES OUBLIÉES

Julia Lermontova   Ellen Gleditsch

1700 — 1800 — 1900

NOMENCLATURE & CLASSIFICATION

1869 1870 1898 1907

THE PIONEERS OF CHEMISTRY

Mikhail Lomonosov
(1711-1765)
Law of Conservation of Mass

Henry Cavendish
(1731-1810)
Discovery of Hydrogen (1766)

Joseph Priestley
(1733-1804)
Discovery of Oxygen (1774)

Carl Wilhelm Scheele
(1742-1786)
Discovery of Chlorine, Manganese, Oxygen

Antoine Lavoisier
(1743-1794)
Father of Modern Chemistry
Traité Élémentaire de Chimie (1789),
First list of 33 elements,
New chemical nomenclature

Louis-Bernard Guyton de Morveau
(1737-1816)
Chemical Nomenclature Reform

FIRST CLASSIFICATIONS

Johann Wolfgang Döbereiner
(1780-1849)
Law of Triads (1817)

Groups of 3 similar elements

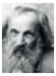
Alexandre-Émile Béguyer de Chancourtois
(1820-1886)
Telluric Screw (1862)

First 3D periodic classification

John Newlands
(1837-1898)
Law of Octaves (1864)

THE CONTROVERSY MENDELEEV & MEYER

Dmitri Mendeleev
Presentation of the Periodic Table March 6, 1869



Lothar Meyer
Periodic curve of atomic volumes

THE QUANTUM REVOLUTION

The Periodic Table as we know it tells only part of the story. Behind its neat rows and columns lie centuries of ignored knowledge from the women who shaped it in silence, to the civilizations whose wisdom was never acknowledged.

Julia Lermontova

Ellen Gleditsch

Stefanie Horovitz

The Invisible - Women who shaped the Periodic Table

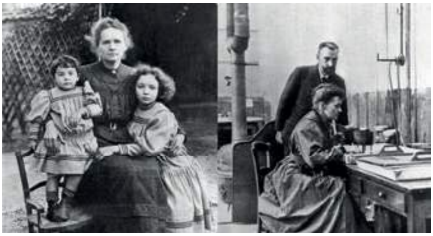
From *Marie-Anne Lavoisier* (1758-1836), who managed the laboratory work behind the first list of 33 elements, to *Julia Lermontova* (1846-1919), close collaborator of *Mendeleev*, *Harriet Brooks* (1876-1933), who first observed radioactive decay transforming one element into another, *Stefanie Horovitz* (1887-1942), who demonstrated the existence of isotopes in 1914, and *Helen Gleditsch* (1873-1963), who confirmed them in 1916. *Ida Noddack* (1896-1978) co-discovered Rhenium (element 75) and first suggested nuclear fission in 1934. *Lise Meitner* (1878-1968) provided its theoretical framework, enabling the discovery of transuranium elements — yet *Otto Hahn* alone received the Nobel Prize. *Marie Curie* discovered Polonium (84) and Radium (88), her daughter *Irène Joliot-Curie* created the first artificial elements, and *Marguerite Perey* discovered Francium (87) in 1939. *Maria Goeppert Mayer* explained the stability of elements through her nuclear shell model, spending years working without salary, dismissed as «just a professor's wife.»

And these are only the women we know about. For every name recorded, how many others were erased before history had a chance to remember them?

«Science is not a man's game, it is a human game»

Gitanjali Rao

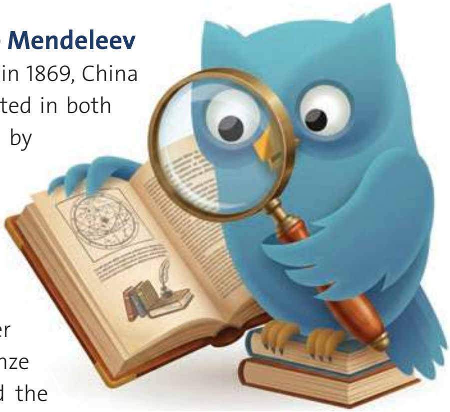
Ida Noddack



Marie Curie and her daughters

William Ramsay

Chinese Chemical Wisdom: Centuries Before Mendeleev



Long before *Mendeleev* published his Periodic Table in 1869, China had developed a sophisticated **proto-chemistry** rooted in both practical needs and philosophical thought. Guided by Taoist alchemy and the theory of the Five Elements (*Wuxing*: Wood, Fire, Earth, Metal, Water), Chinese scholars sought to understand and transform matter through dynamic cycles rather than fixed atomic structures. This unique framework led to remarkable achievements: the invention of gunpowder (**huǒyào**) as early as the 9th century, mastery of bronze and iron metallurgy since the *Shang dynasty*, and the creation of fine porcelain through advanced firing and glazing techniques. Far from being mere empirical practice, Chinese proto-chemistry foreshadowed key modern concepts such as chemical equilibrium and reversible reactions. When the Periodic Table finally reached China in the late 19th century, brought by missionaries and returning students, Chinese scholars seamlessly integrated their centuries-old knowledge into this new scientific framework, a testament to the universality of chemistry across cultures.

Arab Chemistry: The Golden Age of Science Before Mendeleev

Long before the Periodic Table was conceived, Arab scholars of the Islamic Golden Age (8th–13th centuries) laid the foundations of what would become modern chemistry. Building on Greek, Persian and Indian knowledge, they transformed alchemy (al-kīmiyā’) into a rigorous experimental discipline, introducing systematic observation and precise methodology. Pioneering figures such as *Jabir ibn Hayyan* (Geber) developed early laboratory techniques “distillation, crystallisation, calcination” and identified key substances such as sulphuric acid, nitric acid and aqua regia. The physician and philosopher *Al-Razi further* systematised the classification of substances into mineral, vegetable and animal categories, foreshadowing modern chemical taxonomy. Arab scholars also made decisive contributions to pharmacology, metallurgy and the production of dyes and perfumes. When their works were translated into Latin in the 12th century, they profoundly shaped European scientific thought and directly paved the way for the chemical revolution that would culminate in *Mendeleev*’s Periodic Table in 1869.

1767 - 1808
New nomenclature and the beginnings of the periodic table

1767 - 1782: *Bergman* decides to reform the nomenclature to make it more universal; this idea is shared by *Guyton*, who then discusses the subject with *Bergman* and together they come up with a reform that is welcomed by the scientific community of the 18th century.
1789: *Lavoisier*, with the help of his wife, presents his classification containing 33 elements.
1806: *Jane Marcet* anonymously publishes a popular chemical book containing more elements than *Lavoisier*’s classification. The book was a great success.

1808 - 1862
Beginning of classification by atomic weight

1808: *Dalton* introduces the highly impactful concept of atomic weight, making it possible to order elements by increasing atomic weight, which led to the first tables of elements.
1821: *Avogadro* took stoichiometry into account in the combustion reaction of dihydrogen, doubling the atomic weights of many elements.
1827: *Berzélius* specified atomic weights, introduced a systematic nomenclature of elements and contributed to the discovery of many of them.
1817-1829: *Johann Döbereiner* established the first triads of elements, observing that certain groups of atoms had atomic weights linked by an average and similar chemical properties. These observations marked the first step towards the periodic classification of the elements.
1843: *Gmelin* extended the concept of triads by identifying new groupings of elements and introducing the term itself. He also proposed an initial classification of the 55 known elements, ordered according to their increasing atomic weights, thus laying the foundations for a table prefiguring *Mendeleev*'s.
1860: *The Karlsruhe Congress* brought together 125 chemists to resolve the confusion surrounding atomic weights, equivalents and chemical nomenclatures. *Cannizzaro*'s influential speech, defending *Avogadro*'s atomic theory, had a profound influence on chemistry, particularly the later work of *Meyer* and *Mendeleev* on the periodic table.

1862 - 1866
Demonstration of the periodicity of the physical and chemical properties of the elements

1862: *De Chancourtois* was the first to notice the periodicity of the chemical properties of the elements when they were arranged by increasing atomic weight. He proposed a classification of the 60 elements known at the time, spiralling in 16 categories around a metal tube according to their atomic weight.
1863 - 1866: *Newlands* noticed similarities between some of the 62 known elements and that these similar properties were repeated when the atoms were arranged by increasing atomic weight. In addition, he noticed certain flaws in his theory that led him to swap elements that should have occupied the same place, which in turn led him to predict the existence of elements that had not yet been discovered. So it was not *Mendeleev* who first predicted the existence of elements that had not yet been discovered, but *Newlands*.

1864 - 1886
Mendeleev and Meyer's periodic tables

1864 - 1868: In 1864, *Meyer* proposed an initial classification of the elements, highlighting the periodicity of their physical and chemical properties. In 1868, he proposed a revision of his first periodic table, which was then comparable to *Mendeleev*'s table. However, his second proposed table was not published until 1870.
1869: *Mendeleev* presented the periodic table as we know it today. By classifying the elements in ascending order of atomic mass, their properties were repeated in a regular order. By respecting

these periods with all the elements he knew at the time, his table was incomplete. For him, it was out of the question to question his model: if some boxes were empty, it was because elements that were unknown at the time had to be there. He also predicted their properties.

1869 and 1871: *Mendeleev*, for educational purposes, published both volumes of the Principles of Chemistry.

1894 - 1898
The discovery of rare gases not predicted by Mendeleev's table

The discovery of rare gases shook the foundations of *Mendeleev*'s classification. Argon and helium were discovered in 1895 by *William Ramsay* and *Lord Rayleigh*. These elements had not been predicted by the classification. This discovery called into question *Mendeleev*'s concept of the element, since at the time it was said that these elements 'do not appear to have chemical properties'.

1898-1925
Discoveries of new elements and major advances in atomic masses by women

Many women, forgotten by history, took part in the discovery of chemical elements or the measurement of their atomic mass, often using dangerous methods. *Lermontova* helped find the right place for Ru, Rh, Pd, Os, Ir and Pt (1878-1889), *Marie Curie* discovered polonium and radium with her husband and *Becquerel* in 1898, *Horovitz* proved the existence of radioactive isotopes (1914-1916). In 1915, *Gleditsch* determined the half-life of natural radium, and in 1925, *Noddack-Tacke* and her husband isolated one of the rarest metals on Earth, rhenium.

1911-1914
Classification of elements by atomic number

1911-1913: *Antonius Van Den Broek* established the link between each element and a unique nuclear charge, thus introducing the notion of atomic number (Z) as a classification criterion. Inspired by *Rutherford*'s work, he proposed a periodic table based not on atomic masses but on Z, which paved the way for the modern version of the table.
1913-1914: *Henry Moseley* demonstrated experimentally that the frequency of X-rays emitted by elements is proportional to the square of their atomic number (Z). Thanks to this relationship, he confirmed the validity of the classification of elements by Z, corrected certain errors in the periodic table and established a solid scientific basis for the modern classification.

1907-1935
Contribution of the electron to the structure of the periodic table

1907: *Thomson* proposed an atomic model in which the electrons, bathed in a «soup» of positive charge, were organised in concentric circles around the nucleus. He used magnetic analogies to describe this configuration, providing an initial hypothesis on the distribution of electrons prior to *Moseley*'s discovery of atomic numbers.
1913-1923: *Bohr* establishes a quantum theory of the hydrogen atom in which the electrons occupy discrete energy levels indexed by a principal quantum number n, emitting photons during transitions, and proposed electronic configurations according to the Aufbau rule, partially justifying chemical properties such as the valency of carbon; In 1921, he incorporated the azimuthal quantum number l introduced by *Sommerfeld*, modifying the configurations but without resolving all the inconsistencies, particularly for nitrogen, which drew criticism for the lack of rigour in his postulates.
1924: *Edmund Stoner* improved *Bohr*'s quantum theory by introducing the magnetic quantum number ml, linked to the precession of angular momentum in the presence of a magnetic field, thus demonstrating additional stationary states; he established a relationship between the number of electrons and ml, making it possible to explain the electronic configuration of nitrogen and the formation of its three bonds, but his theory still failed to fully explain the spectra observed under a magnetic field.
1925: *Pauli* introduces a fourth quantum number, the ms spin, and formulates the exclusion principle stipulating that two electrons cannot have the same quadruplet of quantum numbers, which explains the multiplicity of spectral lines and the length of periods in the periodic table, but does not yet link these configurations to chemical properties or the order of orbital groups.
1925-1935: Quantum mechanics replaces *Bohr*'s old theory by introducing the notion of orbitals, thanks to the work of *Heisenberg* and *Schrödinger*, making it possible to better describe the electronic configurations and chemical properties of the elements. *Klechkowski*'s, *Hund*'s and *Pauli*'s exclusion rules explain the order in which the electronic sublayers are filled, as for nitrogen ($1s^2 2s^2 2p^3$) and scandium ($1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^1$), justifying the current form of the periodic table.

1.2 The Table Today: Classifying Elements and Unlocking Properties

"As the ultimate compilation of chemical knowledge, the periodic system emerged from the study of substance properties and reactions, shaping the path of chemistry. Today's challenge is to transcend its consolidated structure to spark further innovation."

Pr. Dr. Guillermo Restrepo
Researcher at Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany.

The adventure of the periodic table begins long before its official creation. Since Antiquity, Greek philosophers attempted to understand matter by reducing it to four fundamental elements: water, fire, earth, and air. It would take until the 17th century for chemists to begin identifying true chemical elements. It was in 1869 that Russian chemist Dmitri Mendeleev (and chemists from different regions and time) accomplished the feat that would forever change chemistry. By classifying the 63 elements then known in order of increasing atomic mass and observing the regular repetition of their properties, he designed the first coherent periodic table. His genius lay in his boldness: he deliberately left empty spaces, predicting the existence of yet-unknown elements, such as gallium and germanium which were discovered just a few years later, brilliantly confirming his theory.

How It Works

The periodic table is organized according to a rigorous logic that reflects the internal structure of atoms. Each element is defined by its atomic number (Z), which corresponds to the number of protons contained in the atom's nucleus. This number determines the chemical identity of an element: an atom with 1 proton will always be hydrogen, with 6 protons carbon, and with 79 protons gold. The table is structured around two key organizing principles:

- Periods (horizontal rows): each row corresponds to an additional electron energy level. Moving from left to right, one proton and one electron are added at each step.
- Groups (vertical columns): elements in the same column share the same number of valence electrons (electrons in the outer shell), which gives them similar chemical properties. For example, all elements in column 1, known as alkali metals, react vigorously with water.

This structure reveals a fundamental periodicity: the properties of elements repeat in a predictable manner at regular intervals, like a chemical melody replaying itself with each new period.

The Rules of Classification

The modern table rests on two fundamental pillars:

1. **Atomic weight and atomic number**
   Unlike Mendeleev, who classified elements by atomic mass, the current table orders them by increasing atomic number (from 1 to 118). This correction, proposed by Henry Moseley in 1913, resolved several anomalies and gave the table its definitive logic. The atomic number is an absolute and unambiguous identifier: no two elements can share the same number of protons.

IUPAC Periodic Table of the Elements

Key: 1 **H** hydrogen 1.0080 ± 0.0002 — Atomic number / Symbol / Name / Atomic weight (Abridged standard)

1	2	3	4	5	6	7	8	9
1 **H** hydrogen 1.0080 ± 0.0002								
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.01 ± 0.0001							
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002							
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.07 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]

2. Chemical properties

Elements are grouped according to their shared chemical behaviors, defined by their electronic configuration. Alkali metals in column 1 are highly reactive, soft, and excellent conductors. Halogens in column 17 are strongly electronegative and readily form salts. Noble gases in column 18 are chemically inert, as their outer electron shell is completely full. Transition metals occupying the central block are hard, conductive, and frequently used as catalysts. Finally, lanthanides and actinides, placed separately at the bottom of the table, include rare earth elements and are often radioactive.

10	11	12	13	14	15	16	17	18
								2 **He** helium 4.0026 ± 0.0001
			5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
			13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

The Periodic Table Today

The current table contains 118 officially recognized elements, spread across 7 periods and 18 groups. The four most recently named elements, nihonium (113), moscovium (115), tennessine (117), and oganesson (118), were officially recognized in 2016 by the International Union of Pure and Applied Chemistry (IUPAC), the governing body that oversees the rules of chemical nomenclature worldwide. These heaviest elements are entirely synthetic: they do not exist in nature and can only be created in laboratories, surviving for mere fractions of a second, by bombarding atomic nuclei at extremely high energies in particle accelerators.

The periodic table is not set in stone.

Scientific teams around the world are actively working to synthesize element 119, which would open an entirely new 8th period, a new chapter in this chemical odyssey that never ceases to be written. *From Mendeleev's intuition to modern particle accelerators, the periodic table remains one of the most beautiful maps ever drawn by humanity: a map of matter itself.*

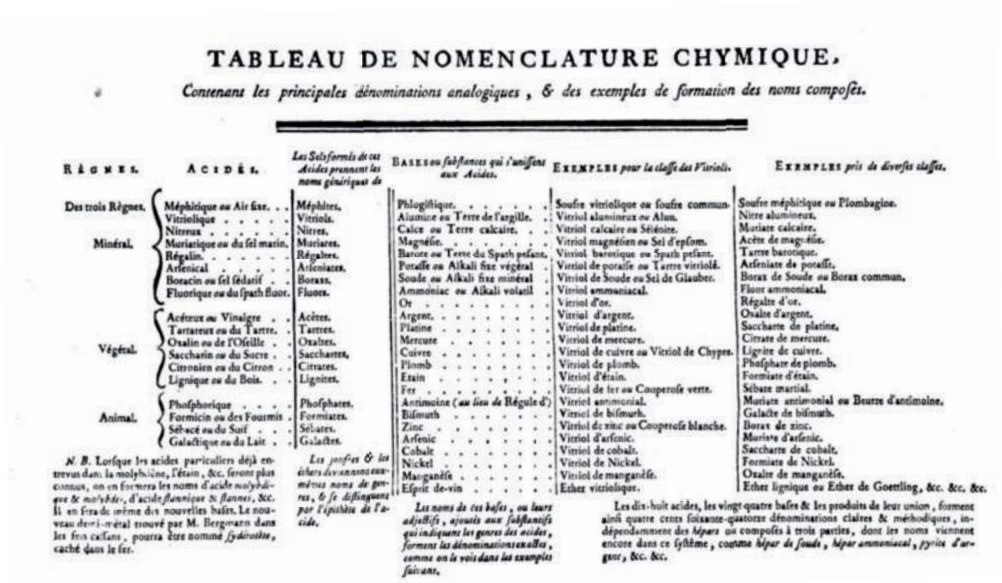


TABLEAU DE NOMENCLATURE CHYMIQUE,

Contenant les principales dénominations analogiques, & des exemples de formation des noms composés.

RÈGNES.	ACIDES.	*Les Sels formés de ces Acides prennent les noms génériques de*
Des trois Règnes.	Méphitique *ou* Air fixe.	Méphites.
	Vitriolique	Vitriols.
	Nitreux	Nitres.
Minéral.	Muriatique *ou* du sel marin.	Muriates.
	Régalin.	Régaltes.
	Arsenical	Arseniates.
	Boracin *ou* sel sédatif	Borax.
	Fluorique *ou* du spath fluor.	Fluors.
Végétal.	Acéteux *ou* Vinaigre	Acètes.
	Tartareux *ou* du Tartre.	Tartres.
	Oxalin *ou* de l'Oseille	Oxaltes.
	Saccharin *ou* du Sucre	Sacchartes.
	Citronien *ou* du Citron	Citrates.
	Lignique *ou* du Bois.	Lignites.
Animal.	Phosphorique	Phosphates.
	Formicin *ou* des Fourmis	Formiates.
	Sébacé *ou* du Suif	Sébates.
	Galactique *ou* du Lait	Galactes.

N. B. Lorsque les acides particuliers déjà entrevus dans la molybdène, l'étain, &c. seront plus connus, on en formera les noms d'acide *molybdique* & *molybdes*, d'acide *stannique* & *stannes*, &c. Il en sera de même des nouvelles bases. Le nouveau demi-métal trouvé par M. Bergmann dans les fers cassans, pourra être nommé *sydérotète*, caché dans le fer.

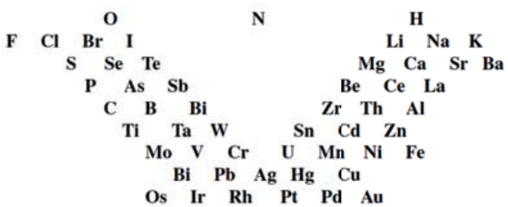
Les pyrites & les éthers deviennent eux-mêmes noms de genres, & se distinguent par l'épithète de l'acide.

BASES *ou substances qui s'unissent aux Acides.*	EXEMPLES *pour la classe des Vitriols.*	EXEMPLES *pris de diverses classes.*
Phlogistique.	Soufre vitriolique *ou* soufre commun.	Soufre méphitique *ou* Plombagine.
Alumine *ou* Terre de l'argille.	Vitriol alumineux *ou* Alun.	Nitre alumineux.
Calce *ou* Terre calcaire.	Vitriol calcaire *ou* Sélénite.	Muriate calcaire.
Magnésie.	Vitriol magnésien *ou* Sel d'epsom.	Acète de magnésie.
Barote *ou* Terre du Spath pesant.	Vitriol barotique *ou* Spath pesant.	Tartre barotique.
Potasse *ou* Alkali fixe végétal	Vitriol de potasse *ou* Tartre vitriolé.	Arseniate de potasse.
Soude *ou* Alkali fixe minéral	Vitriol de Soude *ou* Sel de Glauber.	Borax de Soude *ou* Borax commun.
Ammoniac *ou* Alkali volatil	Vitriol ammoniacal.	Fluor ammoniacal.
Or	Vitriol d'or.	Régalte d'or.
Argent.	Vitriol d'argent.	Oxalte d'argent.
Platine	Vitriol de platine.	Saccharte de platine.
Mercure	Vitriol de mercure.	Citrate de mercure.
Cuivre	Vitriol de cuivre *ou* Vitriol de Chypre.	Lignite de cuivre.
Plomb	Vitriol de plomb.	Phosphate de plomb.
Etain	Vitriol d'étain.	Formiate d'étain.
Fer	Vitriol de fer *ou* Couperose verte.	Sébate martial.
Antimoine (*au lieu de* Régule d')	Vitriol antimonial.	Muriate antimonial *ou* Beurre d'antimoine.
Bismuth	Vitriol de bismuth.	Galacte de bismuth.
Zinc	Vitriol de zinc *ou* Couperose blanche.	Borax de zinc.
Arsenic	Vitriol d'arsenic.	Muriate d'arsenic.
Cobalt	Vitriol de cobalt.	Saccharte de cobalt.
Nickel	Vitriol de Nickel.	Formiate de Nickel.
Manganèse	Vitriol de manganèse.	Oxalte de manganèse.
Esprit de-vin	Ether vitriolique.	Ether lignique *ou* Ether de Goettling, &c. &c. &c.

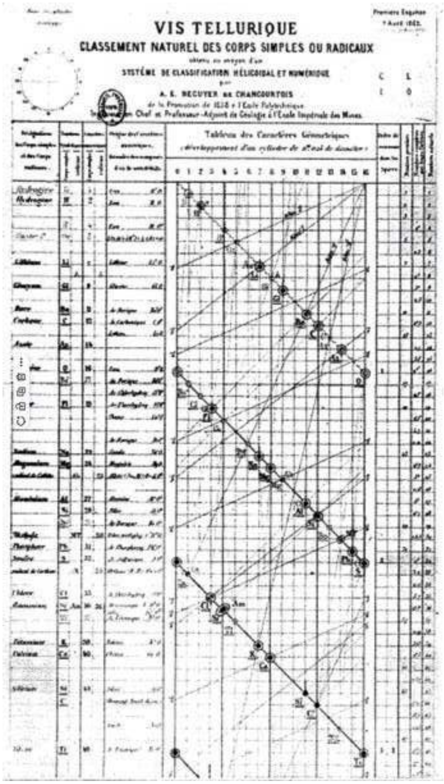
Les noms de ces bases, ou leurs adjectifs, ajoutés aux substantifs qui indiquent les genres des acides, forment les dénominations exactes, comme on le voit dans les exemples suivans.

Les dix-huit acides, les vingt quatre bases & les produits de leur union, forment ainsi quatre cents soixante-quatorze dénominations claires & méthodiques, indépendamment des *hépars* ou composés à trois parties, dont les noms viennent encore dans ce système, comme *hépar de soude*, *hépar ammoniacal*, *pyrite d'argent*, &c. &c.

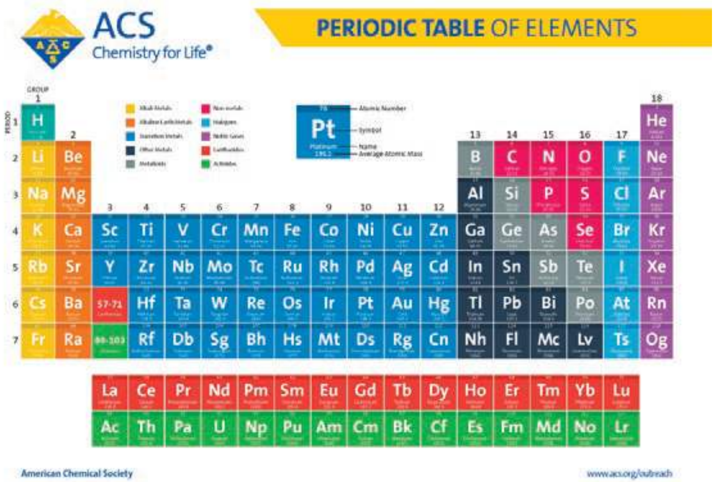
Tableau de nomenclature chimique - Guyton, 1782



Classification des éléments
par Gmelin - 1843



Vis tellurique - De Chancourtois, 1862



An element is not merely
a scientific abstraction:
It is a strategic asset, a potential
health hazard, a geopolitical
lever, and an ecological
footprint all at once.

2

Decoding the Table: New Insights for Today's and Tomorrow's Challenges

The adventure of the periodic table begins long before its official creation. Since Antiquity, Greek philosophers attempted to understand matter by reducing it to four fundamental elements: water, fire, earth, and air. It would take until the 17th century for chemists to begin identifying true chemical elements. It was in 1869 that Russian chemist Dmitri Mendeleev (and chemists from different regions and time) accomplished the feat that would forever change chemistry. By classifying the 63 elements then known in order of increasing atomic mass and observing the regular repetition of their properties, he designed the first coherent periodic table. His genius lay in his boldness: he deliberately left empty spaces, predicting the existence of yet-unknown elements, such as gallium and germanium which were discovered just a few years later, brilliantly confirming his theory.

2.1 Current and future issues

Mendeleev and all chemists gave us a framework. Now we must give it a retrofit. Why Now?

The urgent shift towards green chemistry demands a fundamental rethinking of how we classify, prioritize and use the elements, not just by atomic number, but by availability, sourcing, toxicity, environmental impact, and more globally by their One Health impact. We are living through a paradigm shift. Six of the nine planetary boundaries have already been exceeded, including climate change, biodiversity loss, and chemical pollution. The chemical sector can no longer be assessed through a single lens. As one leading voice in the chemical transition puts it: «CO_2, biodiversity, water, health, resource depletion and the chemistry cycle are one single challenge.» Focusing exclusively on carbon emissions is not only insufficient, it is dangerous.

Global chemical production has multiplied fiftyfold since 1950 and is expected to double again by 2030. Heavy metals contaminate soils and waterways. Rare earth elements are extracted under conditions that raise environmental and human rights concerns. Persistent pollutants accumulate in ecosystems for decades, creating a chemical iceberg whose full extent has yet to be scientifically evaluated. The circular economy, widely celebrated as a solution to resource depletion, is increasingly viewed as a potential vector of circular pollution: the unintended redistribution of toxic substances through recycling loops and recovered waste streams. An element that re-enters the economy through recycling does not shed its toxicological profile. The circular economy is not inherently clean, it must be made so, deliberately and rigorously.

An element is not merely a scientific abstraction: it is a strategic asset, a potential health hazard, a geopolitical lever, and an ecological footprint all at once.

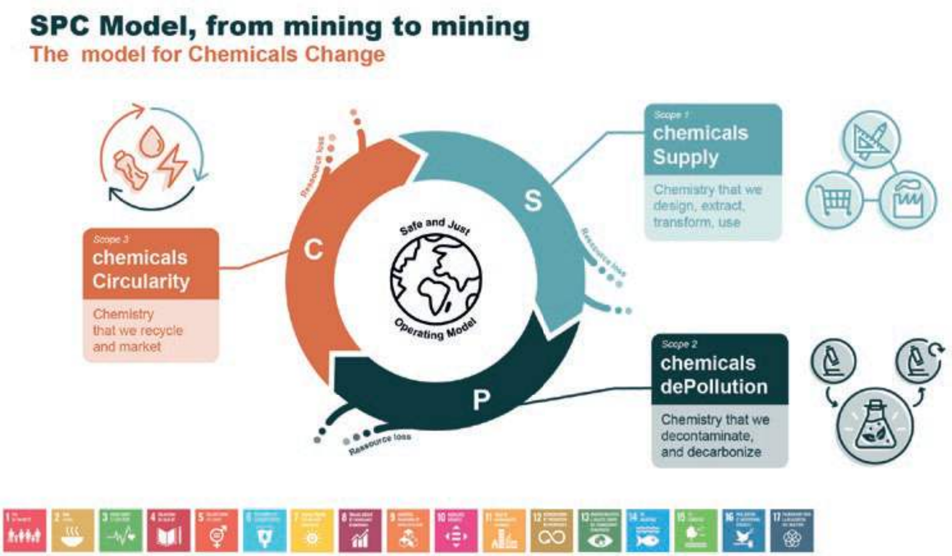
Back to Fundamentals

In 2024, we began with the first fundamental tool of every chemist: the 12 Principles of Green Chemistry, reread and enriched in the light of today's planetary realities. That work raised an inevitable question: if we have rethought how to do chemistry, should we not also rethink with what?

This led us, in 2025, to the second fundamental tool: the Periodic Table itself. **Not to reinvent it, but to reread it with new eyes**, enriched by decades of evidence on toxicity, environmental fate, resource criticality and systemic risk. This is a return to fundamentals, for today and tomorrow. And one principle must anchor this return: **the first and most powerful source of sustainability and prevention is education**. No regulation or technology can substitute for scientists, engineers and citizens who genuinely understand the chemical world they inhabit. **Teaching the periodic table differently, more honestly, more completely, is not a pedagogical detail. It is a strategic act**.

A Map of Responsibilities: The Periodic Table of today and tomorrow is not just a scientific tool. It is a map of our responsibilities, asking, for each element: where does it come from, at what cost, how scarce is it, what are its health and environmental impacts, and could it become

a vector of circular pollution if reintroduced without adequate safeguards?
Just as the SPC model (Supply – déPollution – Circularity) maps the full chemistry cycle from mine to mine, a reimagined periodic table must map the full impact of each element, from extraction to recycling, leaving no blind spot.
This is about giving scientists, educators, policymakers and citizens a shared, honest, and actionable picture of the chemical world we inhabit and the one we are building for future generations.
This section remains a working draft and is intended as a basis for further reflection and development.



***I. Remonnay, M. Goapper** - 2021*

2.2 Reinventing the Periodic Table A guide for essential chemistry

"Sustainable chemistry invites us to reimagine the Periodic Table beyond atomic structure, incorporating criteria such as availability, environmental impact, and ethical use. Rather than a simple classification tool, it could become a guide for responsible innovation, highlighting renewable, low-toxicity, and recyclable elements while flagging those that are scarce or harmful."

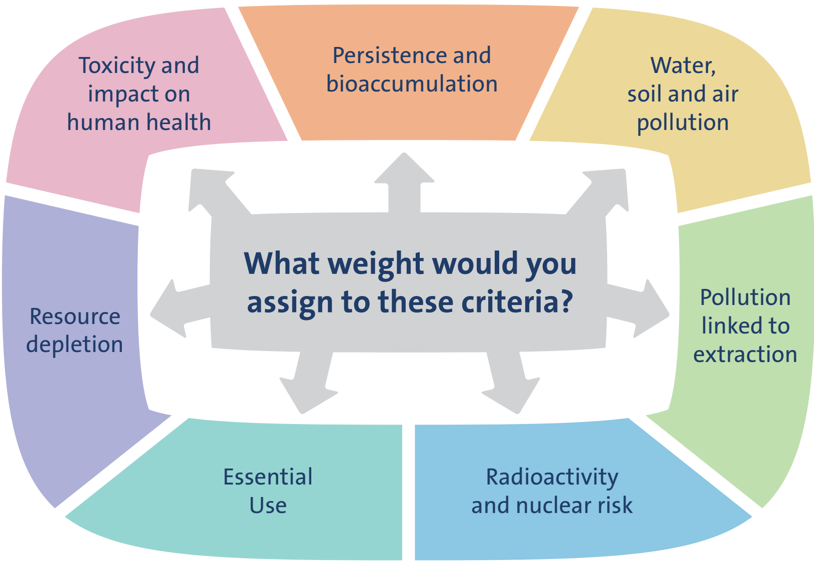
Pr. Youssef Habibi
UM6P Morroco, Professor & Director Sustainable Materials Research Center & College of Chemicals Sciences and Engineering

New Perspectives for Today's and Tomorrow's Challenges

Several key questions arose when approaching this topic. How can we link the elements of the periodic table to their relevance in the ecological, chemical and industrial transitions? And how should they be classified?

The goal is not to create an entirely new periodic table replacing *Mendeleev*'s, but rather to revisit and update it to reflect current challenges. This tool is designed for educational purposes, raising awareness of the environmental and health impacts associated with the use of certain elements. However, it has its limitations: it is molecules, combinations of atoms, that are actually used, and the effects of a given element can vary significantly from one molecule to another. To address this, we have classified chemical elements by taking their most common uses into account. Our literature review identified several categories for classifying these elements. We then organised two round-table discussions. The first aimed to validate these categories or identify additional ones. While our research led us to prioritise certain impacts over others, a broader perspective and external input were necessary to ensure objectivity. Students were therefore invited to freely discuss what they considered the most important factors. The criteria we had previously identified were ultimately the most frequently mentioned, and the final selection later presented to engineering students was validated. The second round table, along with the conclusion of the first, focused on how to design a clear and functional periodic table that effectively presents this additional information, which is the subject of the second part of this work.

Criteria selected at the first roundtable discussion



The criteria we have identified help assess the environmental, health and industrial impacts of these factors, but reality is more complex. These criteria are interconnected and, while based on solid research, involve some degree of subjectivity. The selected criteria are:

- Toxicity and health impact: assessed using GHS chemical classification pictograms and laboratory studies.
- Persistence and bioaccumulation: how long a substance stays in a living organism and how much of it can build up. This accumulation can cause various diseases.
- Water, soil and air pollution: human activities pollute water (wastewater, pesticides, shipping), soil (pesticides, intensive farming) and air (industrial emissions, combustion). This harms biodiversity, the environment and health.
- Extraction-related pollution: based on the life-cycle analysis of a substance in its most common use.
- Radioactivity and nuclear risks: risks linked to nuclear waste or power plant accidents.
- Industrial and everyday use: substances essential to daily life require closer attention, to find alternatives or limit their use and avoid resource depletion.
- Resource depletion: both an environmental and geopolitical issue, which must be addressed to prevent shortages and conflicts.

Reinventing the Periodic Table:
A Guide to Essential Chemistry - The New Table

⚠ ***Note: This is an incomplete exercise. The following text is a working draft intended to be further developed, refined, and expanded. It does not claim to be exhaustive.***

With a view to developing sustainable materials, new elements are increasingly being mobilised, and the range of minerals requiring extraction is becoming ever more diverse. Given growing demand, the supply of certain raw materials is emerging as a source of geopolitical and economic tension particularly rare metals used in batteries, semiconductors for electronics, and superconductors for quantum computing. The development of materials and technologies thus represents one of the defining challenges of the 21st century, simultaneously scientific, ecological, and economic.
At the heart of this challenge lie materials, and therefore molecules specific arrangements of atoms. We have consequently chosen to focus on the most commonly encountered molecules in order to assess the environmental and health impacts, as well as the supply challenges, associated with the elements of the periodic table.

Existing Approaches and Their Limitations: Various alternative formats for the periodic table have been proposed to illustrate the real-world impacts of chemical elements. However, whilst these representations provide useful information, their format is not always well suited to scientific use or to raising broader public awareness of green chemistry. We make no claim to comprehensiveness, and this work is part of a wider ongoing effort. Several notable examples illustrate both the potential and the limitations of these approaches:

- EuChemS (2019) produced a table highlighting the 90 natural elements, using colour-coding to indicate scarcity risk and box sizes proportional to crustal abundance. Designed to raise public awareness around modern technologies such as smartphones and batteries, it remains focused on a single theme: availability.

- Jenkins, Musgrove & White (2023) proposed a table integrating toxicological and nutritional considerations, classifying elements by their biological role and identifying relevant biomarkers. Whilst valuable for researchers and public health professionals, its scope remains limited and does not lend itself to broader green chemistry awareness.

- A carbon footprint table summarises the climate impact of extracting various elements, measured in CO_2 equivalent per unit of material, again, through a single lens.

A Shared Limitation: These examples demonstrate a genuine effort to communicate the impacts of chemistry on the environment, human health, and industry. Yet each confines itself to a limited number of criteria, typically centred on a single theme. None offers a truly integrated, multi-dimensional perspective on the full complexity of the ecological transition. This exercise remains incomplete and is intended as a basis for further reflection and development.

Our Periodic Table

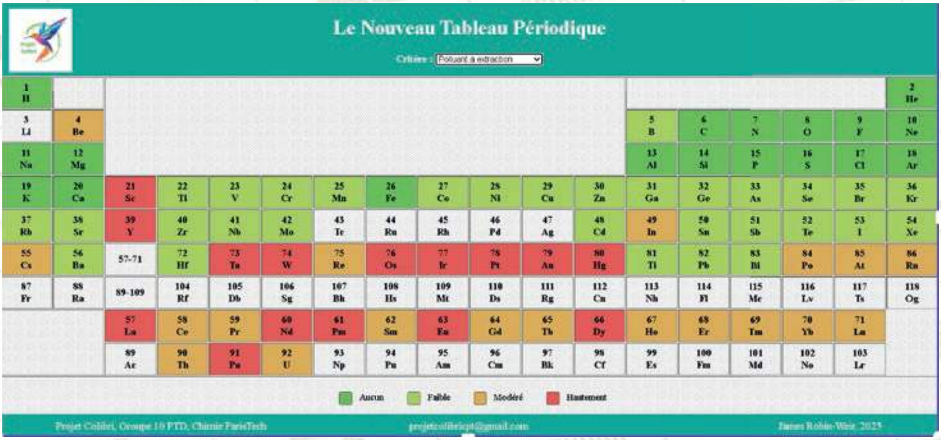
Design Choices: To present the criteria identified earlier in a clear and educational format, three approaches were explored:

- A 3D table, rejected due to implementation complexity and lack of clarity.
- A scoring system inspired by the Nutri-Score, weighting the seven selected parameters partially retained but modified, as determining the relative importance of each criterion proved difficult and inherently subjective.
- An interactive digital table, ultimately chosen, allowing users to access information on each element across the seven criteria with a simple click. This last option was favoured following discussions with both students and researchers, who identified it as the most accessible and adaptable format, particularly given the current pace of digital transformation.

What the Table Shows: The table illustrates the availability of chemical elements, their environmental and health impacts, and the geopolitical issues surrounding them, organised around the seven criteria identified earlier. A colour-coded system reflects a 1-to-4 ranking scale, allowing users to quickly identify patterns. For example, heavy metals, lanthanides, and actinides are readily identifiable as significant pollutants: often extracted from deep underground, they are not easily retained by organic matter, leading to severe environmental contamination through chemical waste, rainfall, and waterways. Elements with no significant impact (category 1) tend to belong to the early periods of the table, as they commonly occur in their atomic state in nature. Synthetic elements are largely absent from the ranking, as they appear almost exclusively in research contexts and those in period 7 often have half-lives of less than a nanosecond, making bibliographic sources scarce. Fields have been left blank where sources were insufficient.

Limitations: It is important to note that an element is not inherently toxic or polluting, it is its role within a molecule that determines its impact. Our classification is based on the molecules in which each element is most commonly found on Earth. For instance, oxygen is not classified as a pollutant, as it is predominantly present as O_2. This table therefore represents a preliminary draft, not an exhaustive classification. Significant further research is needed to make it fully usable by scientists. It is primarily intended as an educational tool for the general public, raising awareness of the impacts associated with the elements of the periodic table.
Perspectives Certain elements remain essential to chemical reactions and industrial processes despite their significant drawbacks, finding alternatives is therefore a major challenge for the chemistry of tomorrow. This table will evolve as research progresses, as resources are depleted, and as new sources are exploited. It is also worth noting that elements are rarely used in isolation: Advanced materials rely on complex combinations, which adds another layer of complexity beyond the scope of this project.

The full interactive table, including all available criteria and sources, can be accessed via the QR code provided above. This exercise remains incomplete and is intended as a basis for further reflection and development.



Screenshot of the website we coded: 12.06.2025

https://projet-colibri.github.io/

3

From Elements to Essentials: Mapping Sciences Priorities

(From key materials to a multidisciplinary vision of science)

"What do "sustainable" or "green" chemistry mean from a regulatory perspective? From a regulatory perspective, «sustainable» or «green» chemistry definitions go beyond pure science, reflecting political and societal choices made by legislators and officials. While science informs these definitions, they may also incorporate policy considerations such as local content requirements or economic development goals. As a result, legal definitions of these concepts will inevitably vary across jurisdictions and evolve over time, unlike scientific principles which remain relatively stable."

Melissa Owen

international Attorney
& Founder
Ambientelegal U.S.

"Chemical sustainability is about context – how do we at a practical level integrate thinking about the numerous dimensions of safety and environmental sustainability into chemical selection decisions – knowing that the answer often starts with ... it depends ..."

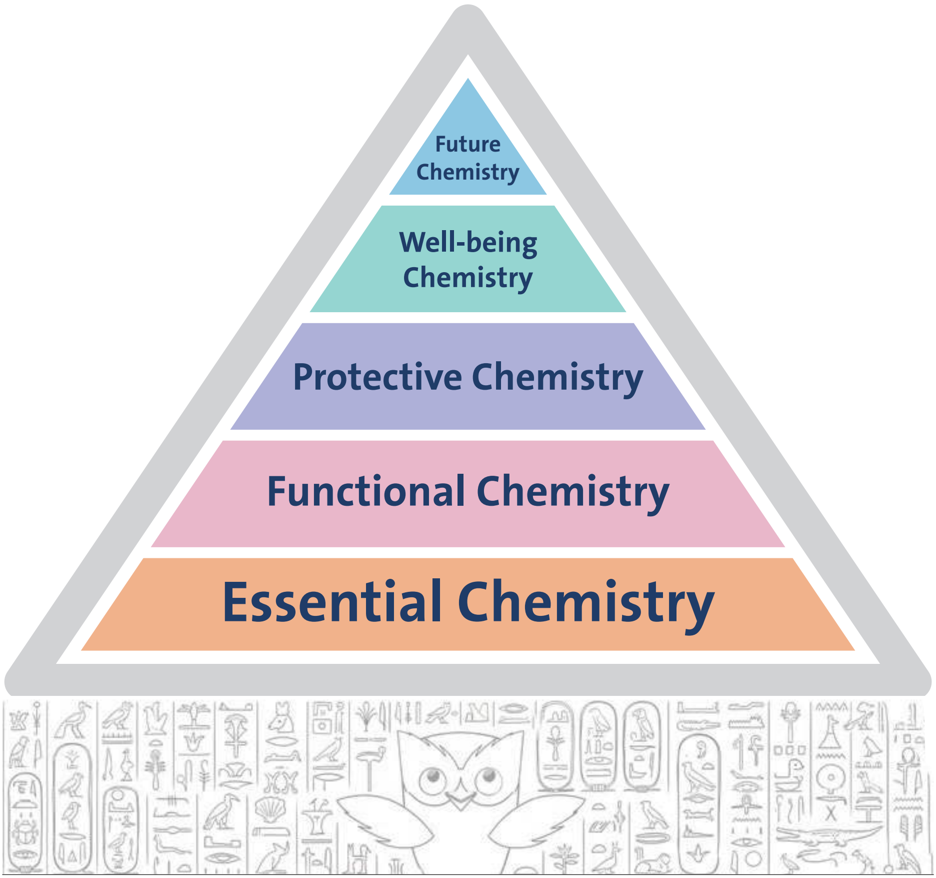
Dr. Eeva Leinala

OEC Principal Administrator,
Environment Health and
Safety Programme,
Environment Directorate

During our work on the Periodic Table, a question was raised: **which substances are truly essential in building our world and shaping our future?** This led to two complementary lines of thought:

- First, we imagined a **'Chemical Maslow Pyramid'** to hierarchize fundamental chemical needs—from sand, salt, iron, copper, phosphore, oil, to lithium—helping us distinguish what is truly vital for life and society.
- Second, we asked how the concept of the periodic table could be extended beyond chemistry, into biology, physics, mathematics (and AI), **as a fractal model to visualize priorities and connections across disciplines**.

These ideas are far from finalized; they represent only the beginning of our reflections. The question remains: "**what should we call it—Green Chemistry, Sustainable Chemistry, Essential Chemistry, or something else entirely?**"



3.1 Chemical Maslow Pyramid: From Needs to Essentials

During our work, it became clear that focusing on fundamental elements is crucial — sand, salt, iron, copper, oil, and lithium — the substances that built our world and will shape our future. This led us to imagine a **Chemical Maslow Pyramid**, a framework to hierarchize what is truly essential for life and innovation, distinguishing between basic chemical needs and advanced materials. Inspired by Maslow's hierarchy of human needs, this pyramid proposes a reflection on how chemistry supports our societies, inviting us to reassess the relative importance of elements from the periodic table and to question how value, necessity, and innovation are defined. It marks the beginning of a broader discussion rather than a fixed hierarchy. This pyramid is structured into five levels, mirroring Maslow's hierarchy of human needs:

- **Essential Chemistry (Vital & Fundamental Needs)**: the foundation of the pyramid: water, minerals, basic elements, and molecules that sustain living systems and biological processes. This includes the elemental building blocks of life CHONPS (carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur), as well as water and salt.

- **Functional Chemistry (Everyday Needs)**: the chemistry of essentials that supports everyday life—feeding, clothing, and housing—through agriculture, construction materials, energy, and basic industrial processes. Iron and steel, cement, glass, fertilizers, and polymers form the material backbone of daily life.

- **Protective Chemistry (Health & Safety)**: Chemistry that protects and preserves life, including pharmaceuticals, medical materials, sanitation, energy security, and defense-related technologies. Active pharmaceutical ingredients, disinfectants, alloys, and fuels play a critical role in maintaining collective safety and resilience.

- **Well-being Chemistry (Comfort & Quality of Life):** Chemistry that enhances quality of life, enabling mobility, connectivity, consumer goods, electronics, and modern conveniences. Copper, silicon, plastics, batteries, and composite materials underpin contemporary lifestyles.

- **Future Chemistry**: The apex of the pyramid, driven by advanced materials, artificial intelligence, clean energy, critical resources, and emerging technologies shaping tomorrow's world. Lithium, rare earth elements, semiconductors, catalysts, and next-generation materials will define future innovation and autonomy.

The Chemical Maslow Pyramid reminds us that the most advanced technologies are always rooted in fundamental chemical needs: innovation rises from survival, and the future is built upon essential matter.

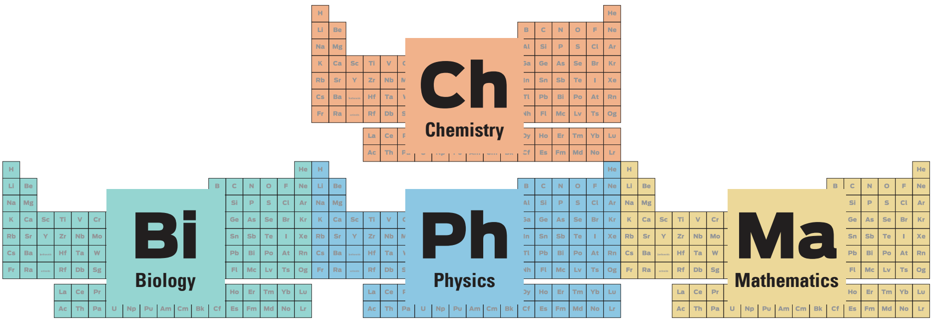
3.2 The Fractal Periodic Table: Extending Chemistry Across Sciences

"The groundbreaking technologies that will shape the future, in particular the environmental transition, are rooted in today's advances in fundamental science. Conceiving new concepts and new materials demands an intimate dialogue between the art of transformation of chemistry and the foundational grammar of physics, from the quantum infinitesimal to the immense."

Pr. Lyderic Bocquet

Physics Research Director, CNRS Professor at the École Normale Supérieure - Paris, France.

The periodic table of chemistry serves as a root model that can be extended to other disciplines. **Why not create a 'periodic table' for biology, physics, mathematics (including AI), and beyond?** This fractal approach helps visualize the connections between sciences, identify priorities, and guide sustainable innovation. Each discipline becomes a periodic system inspired by chemistry, revealing what truly matters and how knowledge across domains interlinks.



The Journey continues...

SUSTAINABLE CHEMISTRY NoteBook 3

COMING SOON

The Chemical Maslow Code: From Essential Molecules to Intelligent Chemistry

...

“In Volume 3, we invite you to explore the newest element in chemistry’s evolution: the intelligent algorithm—where “Sustainable AI-driven chemistry and Chemistry-driven AI” become two faces of a single coin, helping us construct a Chemical Maslow Pyramid that ensures every material, from the most basic to the most advanced, serves both humanity and the planet.”

陈湫帆 **Stanley Qiufan CHEN**

And the baton is shared...

"Roots remain,
branches move
—**the baton is shared**.
Collaboration begins
done is better than perfect!
Join us to rethink
chemistry education
and the future
of chemistry with **people**"

The Chemical Notebook – Advanced Materials for Industrial and Technological Sovereignty: Sustainable and Green Chemistry: From Foundations to Industry 5.0

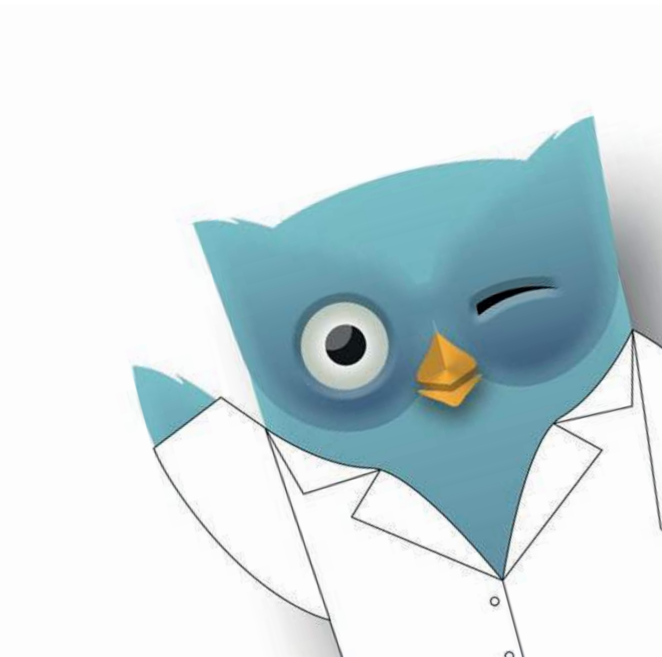
Pr. Youssef Habibi
UM6P Morroco, Professor & Director Sustainable Materials Research Center & College of Chemicals Sciences and Engineering Green ChemAfrica

The Chemical Notebook: Safe Chemistry for One Water, One Health - Sustainable and Green Chemistry for Islands of Life

Dr. Kirk Douglas
Director Centre for Biosecurity Studies
The University of the West Indies Barbados

Education is a key lever to accelerate the chemical transition: by training students, professionals and organisations, we can turn green chemistry principles into concrete industrial practices.

Grégory Chatel
Director of the Chimie Verte Academy
Associate Professor, Université Savoie Mont Blanc



Veolia – mise en page : Studio 46 – impression : Quarante-six – 2026