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Using waste as resource to realize a circular economy: Circular use of C, N and P
J. Chris Slootweg

Chemistry traditionally focuses on converting resources into product, which resulted in the development of a plethora of synthetic methodologies creating a vast amount of molecules and materials that are currently used in society. This linear production model, however, has created a lot of waste that also enters the environment creating local, and also global, major environmental problems. This provides a new role for chemistry, one that focusses on the development of new recovery and recycling processes to advance the efficient use of resources, as well as the development of novel synthetic methods that use waste as resource.

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Introduction
The year 2019 was the International Year of the Periodic Table (#IYPT2019), where chemists celebrated the 150th birthday of the Periodic Table of Chemical Elements in the format proposed by Mendeleev in 1869 [1–7]. The European Chemical Society (EuChemS) created for the occasion a special representation of the periodic table that highlights element scarcity (Figure 1) [8]. EuChemS hereby emphasizes that ‘we have to use our precious resources with much more care in the years to come, and we need to carefully look at our tendencies to waste and improperly recycle such items. Unless solutions are provided, we risk see many of the natural elements that make up the world around us run out — whether because of limited supplies, their location in conflict areas, or our incapacity to fully recycle them’ [9*]. This means that from now on, we have to fully grasp the issue of element scarcity and take action to realize element circulation. Conservation of our elementary building blocks can only be carried out by recovery and recycling them after their use [10–13]. The development of chemistry that enables the circular use of our elements, molecules and materials is therefore key [14**,15**], next to preventing chemicals from entering the environment [16,17], and thus avoiding them to cause pollution [18]. Safe and circular by design of molecules and materials for a sustainable future is thus of utmost importance [19*,20]. Inducing such change from the current linear ‘take-make-dispose’ model to a more circular one requires a holistic approach [21**–23] to design a new system of using and reusing our precious elements.

Waste as resource
There is obviously plenty of waste available for use as resource materials but where to start? The most stringent waste problems are addressed by the nine planetary boundaries of Steffen, Rockström et al. [25**,26], which are: climate change, loss of biodiversity, ozone depletion, ocean acidification, biogeochemical flows (the flow of nitrogen and phosphorus), land-system change (deforestation), fresh water use, atmospheric aerosol loading and chemical pollution (Figure 2). Shockingly, society’s activities have pushed four of these sustainability targets beyond the boundaries into unprecedented territory, namely: extinction rate (one of two indicators for biosphere integrity), atmospheric carbon dioxide (an indicator for climate change), and the biogeochemical flow of nitrogen and phosphorus, of which the latter three can be solely ascribed to the chemistry of three elements: Carbon, nitrogen and phosphorus. Urgent action therefore needs to be taken to return to safe operating space in these processes.

The focus of this short review is, therefore, on these three elements (C, N, and P) that are key players in the suite of major biogenic elements, often termed ‘CHONPS’, needed in large quantities to make living organisms, as well as contribute heavily to three of the most stringent environmental concerns (Figure 2). Interestingly, the EuChemS periodic table (Figure 1) highlights that element scarcity is far from alarming for C, N, and perhaps to a lesser extent for P [27]. The planetary boundaries concept teaches us clearly that next to advancing resource management, sustainable chemistry is also urgently required to tackle environmental waste issues. So what are the waste products that enter the environment? For carbon, this mainly concerns the greenhouse gases carbon dioxide and methane that are expelled to the atmosphere. The nitrogen waste issue is caused by nitrogen oxides (N₂O, NO₃) and
predominately ammonia (NH₃) that are discharged into the aquatic environment and/or atmosphere. For phosphorus, it concerns phosphate, which is next to ammonia essential for plant growth, yet this building block of life also ends up in aquatic systems causing eutrophication [28].

**Carbon**

The negative impact of carbon dioxide on climate change [29] can be reduced by decreasing carbon emissions caused by the burning of gas, oil, coal and biomass for energy production and advancing cement production [30,31], but also by removing CO₂ from the atmosphere by carbon capture [32,33] or even direct air capture [34]. Subsequently, CO₂ is available for recycling, which is established for the synthesis of high-value specialty chemicals [35–37], yet only a few industrial processes use CO₂ as resource [38]. The challenge, though, is to develop novel methods for CO₂ recycling that aim to compete with petrochemistry for the synthesis of bulk chemicals [39, 40*]. In this respect, converting CO₂ into CO is considered as an attractive approach because CO can be readily utilized as a feedstock for value-added chemicals and fuels through the existing downstream thermochemical reactions [41,42]. In addition, methane also contributes significantly to climate change, as it is a roughly 30 times more potent greenhouse gas than CO₂. Therefore, the use of methane as resource for the production of value-added products is also of great interest [43*,44]. Particularly appealing is methane dry reforming with CO₂, thus using both greenhouse gases, to produce...
syngas (CO + H₂) directly, which was recently made possible at room temperature using thermally stable and highly selective photocatalysts [45*]. These recent developments are promising and will help creating a carbon reuse economy [46], particularly using renewable energy [47].

Nitrogen
Managing the nitrogen issue to sustain food production and the environment [21**,48*] is effective by advancing ammonia synthesis [49–54] and to reduce nitrogen discharge from livestock, domestic and industrial sources [55] and to restore water quality [56]. Current efforts to reduce pollution through wastewater treatment [57,58] and by improving cropland nitrogen management can remedy this situation. Interestingly, anaerobic ammonium oxidizing (anammox) bacteria own a central position in the global N-cycle, as they have the ability to oxidize ammonium (NH₄⁺) to N₂ under anoxic conditions using nitrite (NO₂⁻) [59]. Next to being indispensable in marine ecosystems [60], the anammox process is also a sustainable way of removing ammonium from effluents and ammonia from waste gas. Because ammonia is a key fertilizer component, recovery and recycling, instead of decomposition into N₂, can greatly improve the sustainable use of nitrogen as it alleviates the environmental burden of ammonia as well as creates locally new (renewable) N-resources that can be reused efficiently [61,62].
Phosphorus
The third element discussed herein that is wasted on large scale is phosphorus. Therefore, it is also key to close the phosphorus cycle [63,64*,65*]. Interestingly, Hennig Brand first discovered the element of phosphorus in 1669 by converting phosphate waste from human urine into white phosphorus (P₄), before fossil phosphate rock was primarily used as resource for the production of fertilizers, feed and food additives, and many more phosphorus-containing chemicals. To realize the sustainable use of phosphorus, we have to follow in the footsteps of Brand and advance phosphorus recovery and recycling by using phosphate waste as resource [66–68]. Next to reducing the environmental impact of eutrophication, this will also provide a local source of renewable phosphates that reduces dependencies on import from elsewhere. To realize a circular phosphorus economy, the biggest challenge is to steer the development and implementation of phosphorus recovery and recycling techniques in such a way that the recovered phosphate waste is always suited for use as resource enabling its recycling into marketable products. Struvite (MgNH₄PO₄·6H₂O) is an interesting candidate in this respect, as it can be produced in good purity and it recovers both phosphorus and nitrogen from the environment [28,69,70]. Recently, also other promising means of capturing ammonium and phosphate ions together were developed [71,72], which bodes well for the future. These emerging technologies showcase that reuse of water pollutants by extracting carbon, nitrogen and phosphorus from wastewater is feasible and, at the same time, generates renewable resources and saves energy [73*], underlining the potential of improved nutrient recovery and recycling [74].

Conclusions and outlook
It is clear that chemistry needs to adjust its focus on prime resources and also incorporate waste as valuable starting material. By optimizing the use and reuse of our all precious elements, so not just carbon, nitrogen and phosphorus, by applying chemistry as enabling tool we can realize a circular economy. This requires circular thinking and systems thinking in the education of current and future leaders [22,75]. All in all, sustainable chemistry is key in the development of a sustainable future and is of immense importance to realize the United Nations Sustainable Development Goals [76*–78].

Conflict of interest statement
J.C.S. is the shareholder and serves as the scientific advisor of SusPhos BV.

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References
Papers of particular interest, published within the period of review, have been highlighted as:
* of special interest
** of outstanding interest

This website offers background information about the EuChemS periodic table.

This article presents some important points on critical elements, including examples, and the importance of adopting sustainable practices in the use of all elements of the periodic table.

This commentary coins the term Circular Chemistry and introduces its twelve principles. The concept of circular chemistry aims to replace today’s linear ‘take–make–dispose’ approach with circular processes, which will optimize resource efficiency across chemical value chains and enable a closed-loop, waste-free chemical industry.

This article highlights various ways how to integrate chemistry into a circular economy.

This study highlights that products, feedstocks, and manufacturing processes will need to integrate the principles of green chemistry and
green engineering, including systems thinking and systems design at the molecular level.


This study highlights that, thus far, the primary activities of chemistry have been analysing, synthesizing and transforming matter. A systems thinking approach in chemistry education is a key asset to develop the molecular basis of sustainability and to integrate knowledge about the molecular world with the sustainability of Earth and societal systems.


This report provides an updated and extended analysis of the planetary boundaries framework, introduced in 2009, and highlights essential targets to sustain planet earth.


This study presents the most efficient and selective molecular electrocatalyst for converting CO2 to CO known at the time that can catalyse the eight-electron reduction of CO2 to methane upon visible light irradiation at ambient temperature and pressure.


This report shows that a simple cerium salt paired with an alcohol can catalytically transform simple hydrocarbons into reactive radicals at room temperature.


As syngas is an extremely important chemical feedstock composed of carbon monoxide and hydrogen, this study shows that syngas can be generated through methane (CH4) dry reforming with CO2 with high light energy efficiency when illuminated at room temperature.


This study applies the green chemistry and green engineering principles to address the main P sustainability challenges, which will facilitate to close the global P cycle.

65. Withers PJA: Closing the phosphorus cycle. Nat Sustain 2019, * 2:1001–1002. This piece highlights that phosphorus recovery is as important for closing the phosphorus cycle as its discovery 350 years ago was for food production.
