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Reducing the Environmental Impact of Solvents for Catalytic Reactions

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The present state of research on catalysis for sustainable chemistry

Ever since the birth of Green Chemistry, there has been a focus on increasing the sustainability of chemistry by reducing waste. Catalysis has since made impressive advances in maximizing the selectivity of reactions and minimizing the waste from stoichiometric reagents [1]. More recently, there have been further improvements by the use of photo- and electrochemistry to carry out "reagentless reactions" [2]. Nevertheless, large volumes of waste in pharmaceutical, speciality and fine chemicals manufacture originate in the solvents used in the processes and for the purification of the products [3]. Not only can the solvents sometimes be toxic compounds, for example, chlorinated organics, but most are also hydrocarbon-based and pose flammability and environmental hazards.

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Even the use of water as a solvent can be problematic as it is costly to clean traces of organic substrates from the water before it can be safely discharged into the environment. Therefore, there remains a pressing need for reducing solvent waste to create more sustainable chemical manufacture via catalysis. Here, we suggest one possible way forward, linked to efforts for mitigating climate change.

Our recent research contributions to catalysis for sustainable chemistry

We have pioneered the use of supercritical carbon dioxide ($scCO_2$) as a solvent for chemical reactions and devised methodologies for high-pressure continuous catalytic reactions on laboratory and larger scales. CO_2 becomes supercritical above its critical point of 30.9°C and 73.8 bar. $scCO_2$ has relatively low solvent power (similar to that of an alkane) and, in general, the solubility of a compound increases with pressure. However, $scCO_2$ has several potential advantages as a solvent: (i) CO_2 is very inexpensive compared to most solvents; (ii) solute separation merely requires release of the pressure and purification of the used CO_2 is simpler than purification of typical organic solvents; (iii) CO_2 is miscible with gaseous O_2 and is completely non-flammable, offering safety advantages for aerobic oxidation reactions [4]; (iv) CO_2 is also miscible with H_2 making it highly suitable as a solvent for hydrogenation. Therefore, our initial work focused on hydrogenation of relatively simple organic compounds with H_2 using a Pd heterogeneous catalyst, with the reactions eventually being scaled up to a 1000-ton p.a. commercial plant [5], which was technically highly successful but was rendered uneconomic by steeply rising energy costs for recompressing the CO_2 (see the outlook). However, we demonstrated that $scCO_2$ can offer additional advantages such as in the hydrogenation of levulinic acid to form γ-valerolactone where the high-pressure phase behaviour can be manipulated to separate pure product (Fig. 1) from the co-product H_2O with less energy than would be required for conventional separation by distillation [6].

We have also combined some of the advantages of photochemistry [2] and $scCO_2$ to demonstrate that $scCO_2$ can be used for reactions with photo-generated singlet oxygen ($^1O_2$). The reactions of $^1O_2$ are potentially

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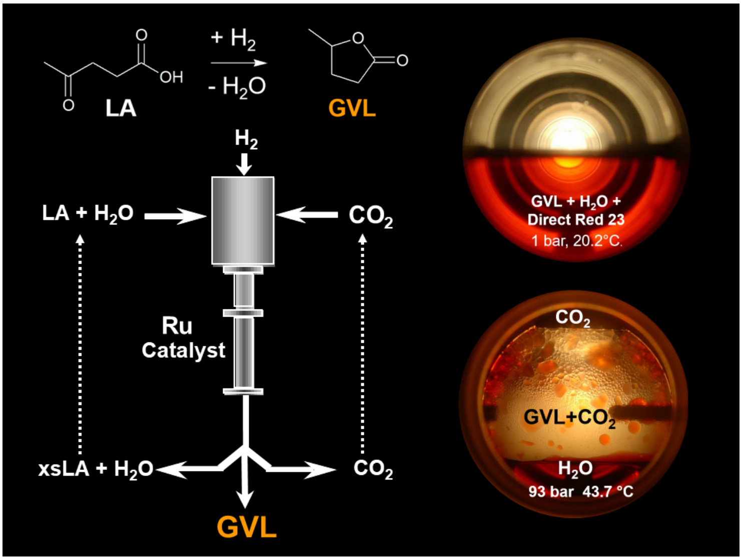

Fig. 1. Schematic of the hydrogenation of levulinic acid (LA) over a ruthenium catalyst to form γ-valerolactone (GVL) in $scCO_2$ using H_2O as the co-solvent and exploiting the pressure-induced phase separation of GVL and H_2O to obtain pure GVL at the output of the reactor. The photos on the right show this phase separation, with a water-soluble dye, Direct Red 23, to highlight the separation of the water more clearly. For more details, see [6].

attractive because of their high atom economy, but, until now, there has been a reluctance to use them on a large scale because of the unstable nature of the intermediate products and the need to minimize the flammability of the solvent. Both of these problems can be addressed by the use of $scCO_2$ in high-pressure flow photo-reactors, which have the additional advantage that $^1O_2$ has a long lifetime in $scCO_2$ [7]. Although our reactors are still relatively small, we have produced a variety of products using $^1O_2$ in $scCO_2$ on scales that are at least an order of magnitude greater than have been previously reported [8]. One example, which involves both $^1O_2$ and an unusual dual-function heterogeneous catalyst, is the semi-synthesis of the anti-malarial drug artemisinin (Fig. 2) using toluene as a co-solvent and eliminating the need for toxic CF_3CO_2H, which is conventionally used as the acid catalyst in this reaction [9].

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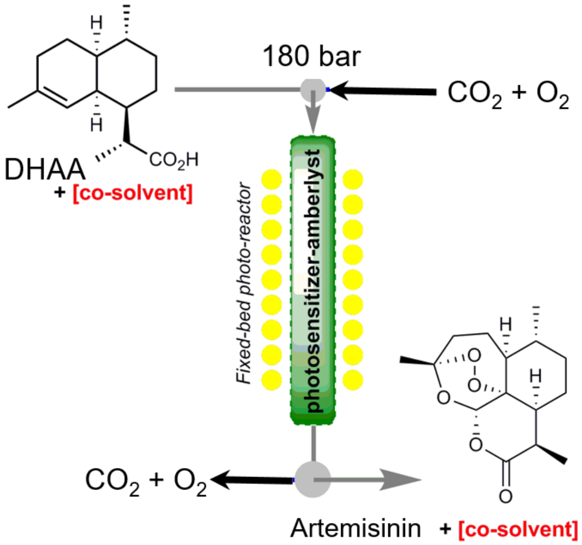

Fig. 2. The photo-oxidation of dihydroartemisinic acid, DHAA, by photo-generated singlet O_2 in $scCO_2$ with a toluene co-solvent to form Artemisinin with the use of a bifunctional catalyst, the photosensitizer tetraphenylporphyrin, immobilized on the acid catalyst Amberlyst 15. Adapted from [9].

We have also shown how such $scCO_2$ flow reactors can easily be automated and combined with AI for self-optimizing catalytic reactions [10].

In addition, we have considered the wider environmental impact of making chemicals and have been inspired by the ideas of Chemical Leasing [11], which proposes that chemical manufactures should recognize that most customers buy chemicals for the effect that those chemicals produce (e.g., coating a surface and treating an illness). This goes against the conventional business model that is based upon the assumption that you will earn more from selling more products. The supplier does not sell quantities of Chemical Leasing, but the supplier sells the performance i.e., the function of the chemical. Thus, by analogy with the electronics industry [12], we proposed Moore's Law for Chemistry, namely that *sustainable chemists should strive to reduce the amount of a chemical needed to produce a given effect by a factor of two, for example within a 5 year*

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cycle, and this process should be repeated for a number of cycles [13]. We build on this concept in the outlook.

Outlook: Future developments of research on catalysis for sustainable chemistry

CO_2 is cheap and abundant and scCO_2 is a solvent with considerable potential for catalytic reactions. At the same time, scCO_2 is beset by the problem of high energy costs for the compression of CO_2. We believe that increasing concerns about climate change offer a real opportunity to resolve this problem. The opportunity lies at the core of some philosophical aspects of Green Chemistry, namely the need to expand the focus from the design of chemical routes and the selection of feedstocks to the wider problems of manufacturing, business models, and supply chains [14]. Our proposal involves Carbon Capture and Storage (CCS) which is increasingly recognized as a key technology, at least in the short term, for decarbonizing not only the energy sector but also other industries (e.g., cement-making or steam reforming to make so-called "blue" ammonia). However, a major barrier to implementation worldwide is that CCS introduces significant additional costs compared to releasing CO_2 into the atmosphere. Therefore, there is a real need for strategies which add value to the captured CO_2 by transforming it into a revenue-earning asset. Thus, one needs to address not only the environmental but also the economic pillar of the triple bottom line [15], a difference between sustainable and green chemistry.

The opening of the 1000-ton p.a. commercial plant [5] in 2002 mentioned above coincided with a large rise in energy prices, a problem which continues to reoccur and impact chemical and other manufacturing. This meant that the energy cost for compressing CO_2 rendered the plant uneconomic to operate. Since then, we have worked extensively in CCS and realized that the key is to combine CCS and scCO_2 solvents [16, 17]. That would make a huge difference because all of the compression costs will be met, as they are already an integral part of CCS. The novelty arises from linking significant potential revenue to what is currently a costly implementation of the net-zero agenda via CCS. It transforms captured

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CO_2 from a worthless waste to a valuable resource without the need to modify the CO_2 itself. This is achieved by exploiting the compression energy stored in captured CO_2 thereby valorizing CO_2 by a physical process that is already inherent to the CCS technology. It tackles one of the key aspects within the circular economy of how to reduce solvent waste — one of the unsolved issues to drive sustainability noting the amount of CO_2 needed to be used for chemical industry is incredibly small compared to the vast amount that needs to be captured. Of course, the captured CO_2 is likely to contain impurities, but we have demonstrated [17] that the predicted levels of impurities for CCS would be acceptable for the type of hydrogenation reaction that we have previously carried out on an industrial scale [5]. Most CCS systems are still at the development stage, so now is the right moment to take a system's view and combine CCS plants with sustainable chemical production by catalysis in $scCO_2$.

Moore's Law for Chemistry (see above) [13] focuses on the effect of chemicals and, in many ways, catalysts are the "ultimate" effect of chemicals. They facilitate transformations that chemists would otherwise struggle to carry out efficiently. Therefore, we propose that, if catalysis is really to help ensure our future supply of chemicals in a sustainable way, we need to adopt and implement Moore's Law for Chemistry. This will need both existing and new catalysts together with future developments to reduce not only the amount of catalysts required but also the quantity of chemicals needed to make those catalysts. That is, we need to reduce over a 5-year cycle by 50% the chemical footprint of a process including the catalysts that we use in the future. This means not only reducing the amount of catalyst needed to promote a given transformation but also halving the amount of chemicals required to make those catalysts. And we need to repeat that 50% reduction over several cycles so that catalysis as well as the whole process can sustainably fulfil the chemical needs of future generations.

We have presented two innovative ideas, namely (i) harnessing CCS to provide a source of CO_2 solvents which can be fed back into the CCS process after use for easy recycling and (ii) applying Moore's Law for Chemistry to catalysts and catalytic processes. Individually, each of these ideas could substantially increase the sustainability of chemical manufacture in the future. Linking them together could be transformative, but

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there is still a need to apply to $scCO_2$ some of the innovations in reactors and processes that we, and others, have already made for continuous chemistry [2] so as to create scalable supercritical photochemical processes. Chemical and other manufacture is now in the throes of a 4th industrial revolution driven by digitization [18], which makes the application of Moore's law to catalytic processes a realistically achievable goal for sustainable chemistry exploiting the ever-increasing application of AI to manufacturing.

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References

[1] R. A. Sheldon, *Green Chem.* **19**, 18 (2017).

[2] M. Poliakoff and M. W. George, *Phil. Trans. R. Soc. A* **378**, 20190260 (2019).

[3] P. J. Dunn, S. Galvin, and K. Hettenbach, *Green Chem.* **6**, 43 (2004).

[4] G. R. Akien, A. O. Chapman, P. Licence, and M. Poliakoff, *Green Chem.* **12**, 310 (2010).

[5] P. Licence, M. Sokolova, S. K. Ross, and M. Poliakoff, *Green Chem.* **5**, 99 (2003) .

[6] R. A. Bourne, J. G. Stevens, J. Ke, and M. Poliakoff, *ChemComm.* 4632 (2007).

[7] R. A. Bourne, X. Han, M. Poliakoff, and M. W. George, *Angew. Chem. Intl Ed.* **48**, 5322 (2009).

[8] L. Q. Wu, B. L. Abreu, A. J. Blake, L. J. Taylor, W. Lewis, *et al.*, *Org. Proc. Res. Dev.* **25**, 1873 (2021).

[9] Z. Amara, J. F. B. Bellamy, R. Horvath, S. J. Miller, *et al.*, *Nat. Chem.* **7**, 489 (2015).

[10] R. A. Skilton, R. A. Bourne, Z. Amara, R. Horvath, J. Jin, *et al.*, *Nat. Chem.* **7**, 1 (2015).

[11] https://chemicalleasing.com (Accessed September 19 2022).

[12] D. C. Brock, *Understanding Moore's Law*, Chemical Heritage Foundation, Philadelphia (2006).

[13] M. Poliakoff and P. Licence, M. W. George, *Angew. Chem. Int. Ed.* **57**, 12590 (2018).

[14] An_Agenda_to_Mainstream_Green_Chemistry.pdf (greenchemistryand-commerce.org) (2015) (Accessed Sept 19 2022).

[15] A. Scerri and P. James, *Int. J. Soc. Res. Methodol.* **13**, 41 (2010).

[16] *Big Ideas for the Future*, RCUK, London, p. 45, (2011).

[17] J. G. Stevens, P. Gomez, R. A. Bourne, M. W. George, *et al.*, *Green Chem.* **13**, 2727 (2011).

[18] P. Bellini, D. Cenni, N. Mitolo, P. Nesi, G. Pantaleo, *et al., J. Ind. Inf. Integration* **26**, 100276 (2022).

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