

Institution: University of Nottingham		
Unit of Assessment: UOA8		
Title of case study: Increasing Public Understanding of Green and Sustainable Chemistry		
Period when the underpinning research was undertaken: August 2000 to present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Sir Martyn Poliakoff FRS	Professor	1979 – present
Michael George	Professor	1990 – present
Steve Howdle	Professor	1990 – present
Peter Licence	Professor	2006 – present
Darren Walsh	Dr	2006 – present
Graham Newton	Dr	2015 – present
Lee Johnson	Dr	2017 – present
Period when the claimed impact occurred: 1 August 2013 to 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		
<p>1. Summary of the impact</p> <p>Research in Green and Sustainable Chemistry has been communicated to a variety of audiences resulting in improved understanding, changed behaviours, and the delivery of educational benefits for students and teachers alike. An award-winning team of researchers has engaged with a local, national and international audience numbering millions of people from over 200 countries that included schoolchildren and teachers, special interest groups, policy makers and the general public. Using a targeted programme of engagement activities (including YouTube videos, TV appearances, exhibitions, science festivals, lectures, and teaching resources) with embedded impact analysis, these interventions have led to measurable changes in understanding. They have also increased awareness of, inspired interest in and altered perceptions relating to the relevance of Green and Sustainable Chemistry to everyday life. All-generations of people have been encouraged to pursue an interest in science and our resources have supported changes in educational practice.</p>		
<p>2. Underpinning research</p> <p>Researchers in the School of Chemistry are acknowledged as pioneers within the field of Sustainable Chemistry. Their research within the Centre for Sustainable Chemistry seeks to develop cleaner, more sustainable processes and materials to satisfy the chemical needs of modern society. Taking place within the UK, this includes research activity in the following topic areas that have formed the basis for our public engagement activities and ensured that the public has gained maximum awareness, understanding and benefit:</p> <p>Alternative solvents: Poliakoff and Howdle have conducted pioneering research on the use of supercritical fluids as a clean alternative to the highly toxic organic solvents that are typically used for chemical reactions and processes. Poliakoff has utilised supercritical water as a medium for performing important oxidation reactions resulting in the clean production of terephthalic acid, a key raw material for the plastic industry [R1, G1]. Howdle has used supercritical carbon dioxide for the clean synthesis of plastics and polymers [R2].</p> <p>Electrochemistry and Photochemistry: George and Poliakoff have developed multiple novel continuous flow reactors that exploit light (photochemistry) and/or electricity (electrochemistry) to promote more specific, efficient chemical transformations and cleaner processes [R3, G2]. By increasing both atom and energy efficiency they have minimised the use of hazardous solvents and achieved low cost, low waste, and shorter manufacturing routes to a range of important chemicals. For example, research on photo-oxidation has been applied to the synthesis of the drug Artemisinin, currently the most effective anti-malarial treatment [R4, G3]. They have developed a highly efficient synthetic route to this molecule that offers the opportunity for widespread affordable access to this vital drug.</p> <p>Clean and Green Polymers: Growing customer demand for more sustainable products is driving a search for new plastics/polymers that are derived from renewable feedstocks, avoiding the use of petrochemical based materials. Howdle has developed a range of novel polymers based upon terpenes that are derived from citrus and wood waste which is available on the multi-tonne scale.</p>		

The research team has invented a new synthetic route to terpene monomers which can be easily converted into polymers. Many scientists have tried to make polymers from terpenes – but Howdle and co-workers are the first to do it with a methodology that could be a “drop-in” to existing industrial processes [R5, G4].

Next Generation Batteries: Batteries with enhanced energy storage and release potential are critical to support the move away from fossil fuels to more sustainable energy technologies. Walsh, Johnson and Newton have conducted research into the chemical composition of the next generation of batteries, including advanced Li batteries and redox flow batteries [R6, G5]. These new technologies are particularly promising for grid-scale energy storage and transportation.

3. References to the research

[R1] Perez, E., Fraga-Dubreuil, J., Garcia-Verdugo, E., Hamley, P. A., Thomas, W. B., Housley, D., Partenheimer, W., and **Poliakoff, M.**, ‘Selective aerobic oxidation of para-xylene in sub- and supercritical water. Part 2: The discovery of better catalysts’, *Green Chemistry*, 2011, **13**(9), 2397-2307. DOI: 10.1039/C1GC15137A

[R2] Goddard, A. R., Perez-Nieto, S., Marques Passos, T., Quilty, B., Carmichael, K., Irvine, D. J. and **Howdle, S. M.**, ‘Controlled polymerisation and purification of branched poly(lactic acid) surfactants in supercritical carbon dioxide’ *Green Chemistry*, 2016, **18**(17), 4772-4786. DOI: 10.1039/C6GC00745G

[R3] Lee, D. S., Amara, Z., Clark, C. A., Xu, Z. Y., Kakimpa, B., Morvan, H. P.; Pickering, S. J.; **Poliakoff, M.**; **George, M. W.**; ‘Continuous Photo-Oxidation in a Vortex Reactor: Efficient Operations Using Air Drawn from the Laboratory’, *Organic Process Research & Development*, 2017, **21**, 1042-1050. DOI: 10.1021/acs.oprd.7b00153

[R4] Amara, Z., Bellamy, J. F. B., Horvath, R., Miller, S. J., Beeby, A., Burgard, A., Rossen, K., **Poliakoff, M.**, and **George, M. W.**, ‘Applying green chemistry to the photochemical route to artemisinin’: *Nature Chemistry*, 2015, **7**(6), 489-495. DOI: 10.1038/nchem.2261

[R5] Sainz, M. F., Souto, J. A., Regentova, D., Johansson, M. K. G., Timhagen, S. T., Irvine, D. J., Buijssen, P., Koning, C. E., Stockman, R. A. and **Howdle, S. M.**, ‘A facile and green route to terpene derived acrylate and methacrylate monomers and simple free radical polymerisation to yield new renewable polymers and coatings’: *Polymer Chemistry*, 2016 **7**(16), 2882-2887. DOI: 10.1039/C6PY00357E

[R6] Ejigu, A., Edwards, M. and **Walsh, D. A.**, ‘Synergistic Catalyst-Support Interactions in a Graphene-Mn3O4 Electrocatalyst for Vanadium Redox Flow Batteries’: *ACS Catalysis*, 2015, **5**(12), 7122-7130. DOI: 10.1021/acscatal.5b01973

Research Grants:

[G1] GR/R02863/01: Poliakoff, M., Howdle, S., George M.; Cleaner Chemistry & Processing In Supercritical Fluids; EPSRC Research Grant; 1/11/2000-31/10/2004; GBP463,865

[G2] EP/P013341/1: George, M., Poliakoff, M., Licence, P., et al; Photo-Electro: Transforming Chemical Synthesis, Discovery and Manufacture; EPSRC Programme Grant; 06/02/2017 – 05/02/2022; GBP6,486,390

[G3] OP/P10702/94: Poliakoff, M., George M.; Bill and Melinda Gates Foundation Grant: to develop a better and cheaper process for manufacturing the anti-malarial drug artemisinin Bill & Melinda Gates Foundation Grant; October 2012; USD231,985

[G4] EP/N019784/1: Howdle, S., Irvine, D., De Focatis, D., Stockman R.; Novel Polymers from Terpenes; EPSRC Research Grant; 01/04/2016 – 30/11/2019; GBP782,562

[G5] FIRG014: Johnson, L., Newton, G., Walsh, D., et al; LiSTAR: Li-Sulfur Technology AcceleratoR; Faraday Institute; 1/10/2019 - 30/9/2023; GBP7,750,000

4. Details of the impact

Despite its centrality to modern society, there is a view that members of the public generally have unfavourable views of chemicals and the chemicals industry. This is partially due to concerns about the chemical industry polluting the world’s ecosystem [I, page 2]. Calls for “greener” and more “sustainable” chemistry, together with attempts to explain the role that chemistry has to play in achieving the UN sustainability goals are a direct response. However, public awareness of the genuine efforts being made to create more sustainable chemical products, processing and practices through research remains limited [I].

Throughout the assessment period, the School of Chemistry has undertaken a sustained programme of public engagement to communicate its world-leading research in Green and Sustainable Chemistry (G&SC), to a global audience of millions including schoolchildren, teachers, special interest groups, policy makers and the general public [A]. This has been achieved through face-to-face events, interactions with schools, TV appearances, and via the internet. These activities have raised awareness, increased understanding, and changed perceptions of the relevance of G&SC to everyday life, as well as encouraging all-generations of people to pursue an interest in science. They have also supported changes in education practice. We have continually evaluated our engagement activities using several methods (including online and paper questionnaires) to determine impact. Evaluation data has been analysed by social scientists specialising in Linguistic Analysis [C] and Public Understanding of Science [I]. Results have confirmed that research communicated through this programme of engagement activity has changed behaviour, though enhancing public understanding and awareness of G&SC.

Online Media and TV Appearances: Research [R1, R4, R5, R6] has been shared with a global audience from over 200 countries via the award-winning YouTube channel, '[The Periodic Table of Videos](#)' (PTOV) and appearances on BBC television and radio. PTOV is a collaboration between Professor Sir Martyn Poliakoff and videographer journalist Brady Haran [B]. In 2019, the American Chemical Society described PTOV as '*one of the most popular science YouTube channels*' in the world. As of December 2020, PTOV had more than 1.45 million subscribers and 247 million views. 8 videos on PTOV specifically communicate G&SC research (4 published pre-August 2013 and 4 post-August 2013) and have received over 1 million views since August 2013. Poliakoff communicated research on the production of Artemisinin using photo-oxidation [R4] through the video '[Fighting Malaria with Green Chemistry](#)' (2015) which had, by 31 December 2020, received 124,937 views. Walsh's research on lithium batteries [R6] featured in the video '[The 2019 Nobel Prize for Chemistry](#)' (2019) which amassed 194,549 views to 31 December 2020. Research into the use of supercritical fluids for application in sustainable chemical processes [R1, R2] features in the videos '[Carbon Dioxide \(Part 1\)](#)' (257,490 total views, 67% of which in assessment period), '[Supercritical Fluids](#)' (397,091 total views, 51% in assessment period), '[Automatic Chemistry](#)' (101,259 total views, 70% in assessment period) and '[Water Bottles and Green Chemistry](#)' (25,060 total views, 25% in assessment period). '[The Professor is Knighted at Buckingham Palace](#)' (2015) (312,443 views), features Poliakoff discussing communicating his research into the production of anti-malarials [R4] with Prince Charles, whilst Licence showcases the unique Carbon Neutral Laboratory for undertaking G&SC research at Nottingham in the video '[Wooden laboratory](#)' (2016) (150,494 views).

An independent linguistic analysis of PTOV comments by Linguistic Profiling for Professionals (LPfP) [C] used methods from *corpus linguistics* to analyse 2,934 online comments associated with the 8 G&SC focussed videos listed above. The analysis found that, '*The viewers are engaged with many of the concepts contained within the videos in the comments section; using these terms [‘chemistry’, ‘laboratory’, ‘malaria’, ‘green chemistry’, ‘automatic chemistry’, ‘carbon dioxide’, ‘supercritical’, ‘fluids’, ‘lithium ion’, ‘acid rain’] at a much higher rate than we’d expect in typical English usage*' [C, page 28, Table 7]. Also, '*Through direct reporting from viewers, there was substantial evidence that the videos have effectively increased public understanding and helped them acquire knowledge. The educational value of the videos manifested in explicit appraisals of the videos as educational, as well as evidence of the videos being used as teaching resources. An additional pedagogical dimension of the channel was identified in which users actively engaged in discussions about the videos’ content and requested and provided their own explanations and clarifications [...]* A consequence of increasing the public's interest and enhancing public understanding of chemistry is that PTOV has also significantly stimulated the public appetite for participating in chemistry in the future and learning about the subject, whether through informal channels or through formal study' [C, page 35]. For example, one viewer comments, "*This is an absolutely fascinating effect [...] it's stuff like this that makes me want to be a chemist*" (Supercritical Fluids, comment 292).

The LPfP analysis also demonstrates the reach of the videos, '*PTOV has provided an openly accessible resource which has increased public interest in chemistry, especially by bringing about*

positive changes to previously-held attitudes towards the subject. Significantly, the channel has been and continues to be engaged with by an extremely diverse variety of groups in society. These span from large, general and non-specialist audiences to highly specialised audiences, such as chemists and those studying the subject in higher education' [C, page 35].

Increasing public exposure to chemistry in informal settings such as news media can raise awareness and understanding of chemistry (*Effective Chemistry Communication in Informal Environments*, The National Academies Press, 2016). On 23 January 2020, the Carbon Neutral Laboratory hosted a live BBC East Midlands Today Climate Change Special that was broadcast to an approximate audience of 687,000 viewers. Walsh, Johnson, Newton and Licence communicated research on plastics, redox flow batteries, and Li-S batteries [R5, R6, G5]. A BBC Correspondent commented '*It's the first time that our main news bulletin has dedicated its full programme to the issue; therefore, it was essential to find an appropriate location to host the live broadcast. After much consideration – including a visit to the building – the laboratory emerged as clearly the best choice. The science taking place on the site is extraordinary*' [D].

Exhibitions: 'Green Light for Chemistry', an exhibit specifically designed to communicate the team's research on photochemistry [R3, R4, G2], was selected to be part of the Royal Society Summer Exhibition 2019 that attracted 9,750 public visitors from across the UK including 1,700 school pupils [E]. After visiting the exhibit, 71% of the surveyed visitors commented that their knowledge of photochemistry and awareness of Sustainable Chemistry had improved. One visitor commented, '*When I explored the exhibit it was a mind-opening experience, demonstrating innovative ways to use light for scientific purposes*' [F]. The exhibit was subsequently selected by the Royal Society of Chemistry to be showcased at the Royal Institution in November 2019 at their 'For Your Inspiration: The Elements of Success' event, designed to inspire ages 12+ into careers in chemistry, and attended by 200 children [G]. The exhibit was also included in Wonder 2019, a free family day held at UoN that attracted 5,000 visitors (26% from widening participation areas) [H].

An independent evaluation of the 486 feedback questionnaires completed by visitors to 'Green Light for Chemistry' by Dr Pryce Davis (University of Nottingham, School of Education), an expert in the public understanding of science, found evidence that the exhibit expanded knowledge and awareness, particularly of sustainable chemical manufacture. The report concludes, '*The responses demonstrate awareness and increasing knowledge of both photochemistry and electrochemistry concepts and the existence of/need for applications to green chemistry. They also demonstrate some level of increasing understanding of the manufacturing process (as evidenced by the mention of the reactors) and products (as evidenced by the mention of specific chemicals)*' [I, pages 9-10].

Public Lectures and Educational Outreach: The team has presented a series of public lectures that showcase G&SC to a wide range of audiences and age groups (12 - 70+), to over 8,500 people [A]. For example, the team has hosted a series of visits to the Carbon Neutral Laboratory for members of the University of the Third Age (U3A) from across Nottinghamshire. Each of these events featured talks on research in sustainable plastics [R5] and the use of photochemistry for the manufacture of antimalarial medicines [R4]. Participants completed a survey before and after the event to assess changes in understanding. Feedback from 226 participants all said their understanding of green chemistry had improved (on average from 4.5 to 8.5 on a ranking system of 1-10). "*Fairly dramatic shifts were seen in the respondents' perceived understanding of sustainable chemistry (Q2) and knowledge of sustainable chemistry research at the University of Nottingham (Q4)*" [I, page 14]. A follow-up survey indicated that 89% of the respondents had shared the knowledge that they had gleaned from the research lectures with others. One respondent explained, "*It made me even more aware of why we should make every effort to live a sustainable lifestyle. I now try to buy sustainable products and check out recyclability and 'preach' to my friends, children and grandchildren*" [I, page 16].

Poliakoff and George were invited to present their research [R4] at the 'Our Future World' series, hosted by the Department for Business Energy and Industrial Strategy (BEIS). The Head of the

Chief Scientific Advisor's Office of BEIS commented: "*It was clear that our packed audience of engineers, analysts, scientists and policy makers found it most thought provoking and highly relevant to the Industrial Strategy.*" Others in the audience commented that the talk provided "*new ways of thinking about the chemical industry*" [J].

The G&SC team have led a range of **educational outreach sessions**, engaging with over 900 teachers and over 2,500 students all over the world (including United Kingdom, Ireland, Germany, Russia, Brazil, Portugal, Australia, China) [A]. For example, Poliakov presented research [R1, R4] at the 61st London International Youth Science Forum 2019 to an audience of 500 students aged 16-21 from 70 countries. Of 181 attendees surveyed, 91% said they were interested to find out more about chemistry and 87% said the presentation had enhanced their understanding of green chemistry [I, page 25].

Two debate style lessons targeted at GCSE and A-Level students and based on Walsh's research on novel batteries [R6, G5] and Howdle's research on sustainable plastics [R5] have been developed and the resources shared on the Times Education (TES) website where they have had over 2,000 downloads since publication in September 2019 (<https://www.tes.com/teaching-resources/shop/CDTSustainableChemistry>). The lessons were designed to inform pupils about the environmental and societal issues around developing new plastics and the electrification of transport. A teacher in Nottinghamshire commented "*most students at the start believed recycling was the only answer but by the end of the lesson they were less convinced*" and "*the lessons challenged conventional wisdom and made the students think more broadly about chemistry and sustainability*" [K].

5. Sources to corroborate the impact

[A] Summary of UoN public engagement activity in Green and Sustainable Chemistry August 2013-December 2020 [PDF]

[B] Periodic Table of Videos – <http://www.periodicvideos.com>

[C] Linguistic analysis of comments found on Green & Sustainable Chemistry PTOV videos, Linguistic Profiling for Professionals (LiPP) [PDF]

[D] BBC viewing figures and letter from BBC journalist Navtej Johal [PDF]

[E] Royal Society Summer Exhibition exhibitors report 2019 [PDF]

[F] Survey of 'Green Light for Chemistry' visitors, Royal Society Summer Exhibition 2019 [PDF]

[G] Invitation (23rd July 2019) and letter of support (5th July 2019) from Royal Society of Chemistry to Sir Professor Martyn Poliakov and Professor Michael George [PDF]

[H] DH Insight, Market Research and Consultancy, Wonder Event Evaluation for the University of Nottingham 2019 [PDF]

[I] Report by Dr Pryce Davis, Assistant Professor in Learning Sciences, University of Nottingham School of Education [PDF]

[J] Letter to Professor Poliakov from the Head of the Chief Scientific Adviser's Office, Department for Business, Energy and Industrial Strategy dated 5th July 2019 [PDF]

[K] Letter of support written to the EPSRC Centre for Doctoral Training in Sustainable Chemistry from a schoolteacher, dated 27th January 2020.