Green Chemistry for Sustainable Development


photo by Andrea Boldizsar on Unsplash

by Pietro Tundo and Elena Griguol*

"We need chemistry to move forward the [UN] 2030 Agenda for Sustainable Development.
We need chemistry to eradicate poverty.
We need chemistry to bolster health.
We need chemistry to mitigate the impacts of climate change.
In a word, we need chemistry for human rights and dignity, to leave no one behind.
Not just any chemistry....
We need green chemistry...sustainable chemistry... chemistry that respects the boundaries of the planet...chemistry that is inclusive, that works for the benefit of all...Indeed, the modern world, as never before, needs green chemistry".

These words were spoken by Irina Bokova, Director-General of UNESCO, in her address to the PhosAgro/UNESCO/IUPAC Award-Giving Ceremony in St Petersburg, 2 June 2017 [1].

IUPAC's concrete answer to this call is the recent establishment of the **Interdivisional Committee on Green Chemistry for Sustainable Development** [2]. ICGCSD supersedes the Subcommittee on Green Chemistry (under the Organic and Biomolecular Division, Div III) founded in July 2001 with the aim of developing actions and projects devoted to the cause of green chemistry for its wider benefit to the future of chemistry and to society as a whole. The Subcommittee was itself preceded by a Working Party on Synthetic Pathways and Processes in Green Chemistry that had been established in 1996. Over the last 15 years, the Subcommittee has completed more than 40 projects. Following the recommendation of IUPAC President Natalia Tarasova, ICGCSD was finally ratified as Standing Committee by the Council at IUPAC General Assembly in São Paulo Brazil on 14 July 2017.

ICGCSD is responsible for advancing the IUPAC strategic plan [3] for green and sustainable chemistry, for assisting the Union in initiating, promoting, and coordinating work in the area of Green and Sustainable Chemistry, and for developing a coherent programme of actions.

The concepts of "Green Chemistry" and "Sustainable Chemistry" have meanings that, while different, are not in contrast with each other, especially in recent times. The two adjectives, "green" and "sustainable," often have a somewhat different connotation according to the country or region where they are used. Currently, Green/Sustainable Chemistry is present in all countries around the world, playing a central role in research, cooperation, initiatives, networks, education, and university courses. The concepts are very well appreciated by professionals, and often represent what people expect with confidence from chemical sciences. More precisely, each country asks chemistry (and chemists) to resolve their own needs; this is a good

OECD "Sustainable Chemistry" (1999)

1. Use of Alternative Feedstocks
2. Use of Innocuous Reagents
3. Employing Natural Processes
4. Use of Alternative Solvents
5. Design of Safer Chemicals
6. Developing Alternative Reaction Conditions
7. Minimizing Energy Consumption

thing because it conveys a very positive image of science in general, and of chemistry in particular.

The Green Chemistry concept was first developed by Joseph Breen, Paul Anastas, and Tracy Williamson in 1998: "The invention, design, and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances." [4] The concept was followed by IUPAC and the main topic of a special issue of the IUPAC Journal *Pure and Applied Chemistry* compiled in 2000 by the Working Party on Synthetic Pathways and Processes in Green Chemistry [5].

Sustainable Chemistry is often also called Green Chemistry, depending on the country and circumstances. The basic concepts of green chemistry are well defined by the twelve principles from the sustainability viewpoint (1998) [4], and by the OECD seven research areas from the applicative point of view of industrial chemical transformations (1999) [6]. These basic concepts haven't changed over the last 25 years and are still valid in their content.

ICGCSD aims to transform the concepts into practical applications by developing novel scientific approaches to the relevant chemical processes and products, for example in the exploitation of renewable resources like bio-masses. In addition, the introduction of green metric procedures and new reaction pathways are necessary to quantify the efficiency or environmental performance of chemical processes and products, as a base for the optimization of manufacturing procedures (for a description of this recently approved project see Project Place p. 31). IUPAC is the only scientific body that can harmonize the correct application of green metrics analysis in syntheses because of its worldwide reputation and influence, and because of its role and responsibility in standardizing nomenclature and terminology in chemistry. ICGCSD believes that innovations in Green Chemistry will continue to have an outstanding role in sustainable global development. ICGCSD activities presently focus on the education of young scientists in green chemistry and on initiating projects to promote new technologies and innovations with less harm to the environment, and suitable to support global social development in accordance with 17 UN SDGs.

Sustainable Development Through Green Chemistry

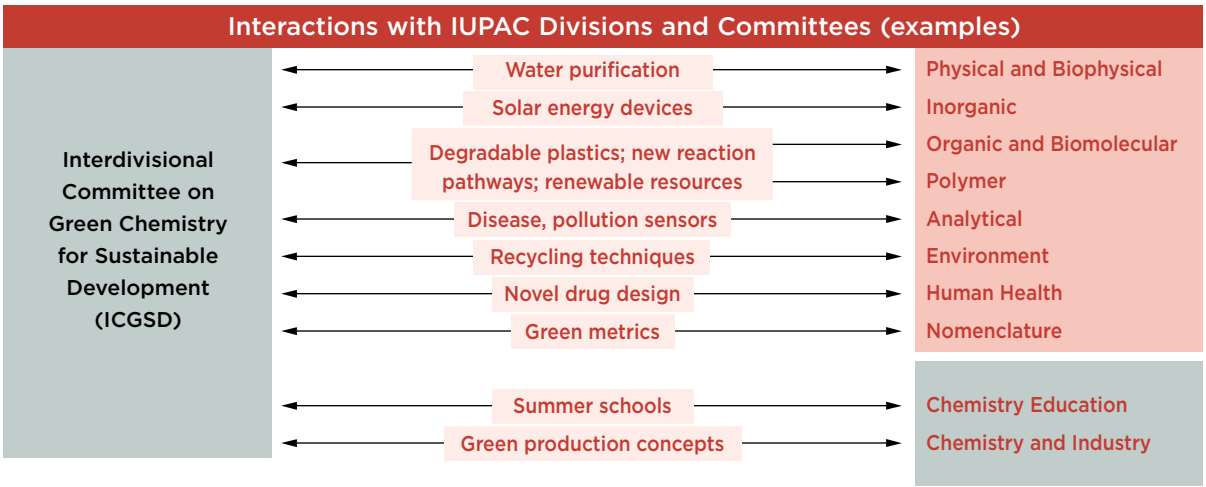
The UN Sustainable Development Goals (SDGs) provide a roadmap for the community to contribute and a clear framework for ICGCSD to help deliver the IUPAC goal of *"Fostering sustainable development"* [3]. ICGCSD plans to submit some initiatives and proposes that Green and Sustainable Chemistry could make a significant contribution to the achievement of the 17 SDGs.

Green Chemistry, in all of its embodiments, can contribute to the realization of these goals; see examples listed above. ICGCSD will seek to unite chemists from different sub-disciplines in multidisciplinary teams to address specific tasks via projects and activities. Improving quality of life through chemical products, *e.g.* by providing citizens with life-saving drugs, cleaner energy, or more sustainable materials, contributes to the UN SDG of poverty alleviation (Goal 1) and can provide a basis for economic growth (Goal 8). Ensuring that Green Chemistry is at the heart of new chemical processes and products will also benefit life (Goal 14 and 15) by reducing resource use. The SDGs related to quality education (Goal 4) and gender equality

U.N. Goals (2015)

What Chemistry can do (examples)

1. Medicines, local solar energy
2. Improved, adapted agrochemicals
3. Drug design, healthcare products, pollution control
4. Courses in green chemistry and environmental sciences
5. Equal gender chances among chemists
6. Water regeneration and purification
7. Photoelectrochemistry, new batteries
8. Recycling, circular economy, long-living products
9. Research on pure and applied chemistry
10. IUPAC networks to underdeveloped regions
11. Novel materials for buildings, bridges, streets, cultural heritage conservation
12. Sustainable manufactures and waste minimization
13. Innovative solar energy systems
14. Marine chemistry
15. Sustainable use of fossils and forests, renewable resource exploitation
16. Support to the Organization for the Prohibition of Chemical Weapons (OPCW)-goals
17. Cooperation with UN, OECD, OPCW, UNESCO and other scientific organizations



constitute key points in IUPAC's agenda. Green chemistry can contribute to healthier, happier communities, with reduced inequality (Goal 10) and stronger institutions (Goal 16). International partnerships (Goal 17) will underpin ICGCSD activities addressing SDGs.

Within IUPAC ICGCSD aims to work actively in collaboration with other IUPAC Divisions and Committees to develop projects in green and sustainable chemistry and to encourage activities in these areas from across them. To foster such collaboration, the membership of the committee includes the formal participation of all IUPAC Divisions and Standing Committees. (see examples in the above table)

Examples of interactions are listed above. In particular, together with the Committee on Chemistry and Industry (COCI) and the Committee on Chemistry Education (CCE), ICGCSD seeks to stimulate and increase interest in green and sustainable chemistry in the theory and practice of industrial chemistry and chemistry education, through their external industrial and institutional relationships.

Collaborating with International bodies ICGCSD will promulgate IUPAC initiatives in the green chemistry field through its collaboration with other international organizations with a common interest. Consequently, it will have important connections and joint initiatives in progress with other international chemical and non-chemical bodies, such as:

- United Nations Educational, Scientific and Cultural Organization (UNESCO)
- Organization for Economic Co-operation and Development (OECD)
- International Sustainable Chemistry Collaborative Centre (ISC3 Federal Environmental Agency UBA - Germany)

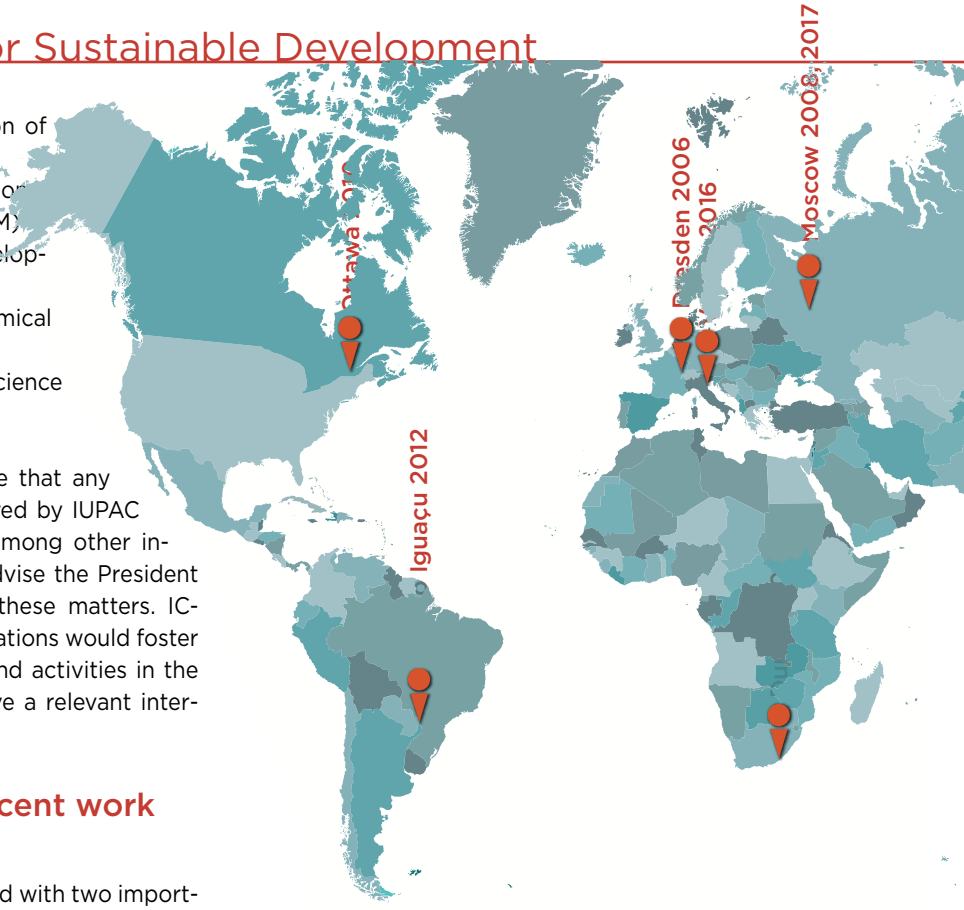
ICGCSD Membership includes the formal participation of all IUPAC Divisions and Standing Committees and –as of 1 Jan 2018– it consists of:

Pietro Tundo* (Italy), Chair
Pierangelo Metrangolo (Italy), Div I, Physical and Biophysical Chemistry
Jorge Colón (Puerto Rico, Div II, Inorganic Chemistry
Janet Scott* (UK), Secretary, Div III, Organic and Biomolecular Chemistry
Christine Luscombe* (USA), Div IV, Polymer
Zoltan Mester (Canada), Div V, Analytical Chemistry
Hemda Garelick (UK), Div VI, Chemistry and the Environment
Michael Schwenk* (Germany), Div VII, Chemistry and Human Health
Fabio Aricò (Italy), Div VIII, Chemical Nomenclature and Structure Representation
Anna S. Makarova (Russia), COCI, Industry
Supawan Tantayanon (Thailand), Chemistry Education
Ekaterina Lokteva (Russia), CHEMRAWN
Wolfram Kock (Germany), Cheminformatics Data Standards
Christopher Brett* (Portugal)
John Corish* (Ireland)
Buxing Han* (China/Beijing)
Natalia Tarasova (Russia), *ex officio* IUPAC Past President

*core members

- Organization for the Prevention of Chemical Weapons (OPCW)
- Strategic Approach to International Chemicals Management (SAICM)
- United Nations Industrial Development Organization (UNIDO)
- International Council of Chemical Associations (ICCA)
- International Council for Science (ICSU)

Such collaborations seek to ensure that any views on green chemistry considered by IUPAC carry the fullest possible weight among other international organizations and to advise the President and the Executive Committee in these matters. ICGCSD believes that fruitful collaborations would foster the realization of future projects and activities in the Green Chemistry field that will have a relevant international impact.



Every two years since 2006, IUPAC has promoted the International Conferences on Green Chemistry (ICGCs). Records of these events are published in IUPAC Journal Pure and Applied Chemistry*; see Note 1.*

Examples of ICGCSD recent work and collaborations

In May 2017, ICGCSD participated with two important contributions in the framework of the **UN Technology Facilitation Mechanism and the upcoming Science, Technology and Innovation Forum for the Sustainable Development Goals** [7] around the following topics:

TOPIC 1: Science, technology, and innovation for the SDGs 1, 2, 3, 5, 9, and 14 [8]

TOPIC 2: STI plans, policies, and capacity building [9]

The discussion aims to mobilize all stakeholders to foster discussion on the SDGs.

In June 2017, ICGCSD contributed to **UNEP**'s call [10] to submit best practices and initiatives in the area of sustainable chemistry pursuant to Resolution 2/7 on the sound management chemicals and waste, which was adopted in 2016 at the second session of the UN Environment Assembly.

ICGCSD Chair Pietro Tundo participated in the **ISC3** meeting held 17-18 May 2017 in Berlin**.** Financed by the German Government, ISC3 was launched during the conference "Mainstreaming Sustainable Chemistry" [11]. The conference provided an opportunity to meet members of the ISC3 global network, which is open to everyone engaged in sustainable chemistry. The conference program covered international political and economic issues of importance for the development of sustainable chemistry. ICGCSD and ISC3 will collaborate on common projects in Green and Sustainable Chemistry, since both ICGGSD and ISC3 support the global breakthrough of Sustainable Chemistry.

More recently, ICGCSD was involved in the preparation and organization of the Workshop on Green and Sustainable Chemistry held at OPCW Headquarters in The Hague, the Netherlands 16-17 November 2017 [12]. The workshop was dedicated to Green Chemistry for non-toxic substitutes and brought together stakeholders from industry, academia, and other backgrounds, providing a useful opportunity to discuss this important matter from different perspectives, as well as to highlight case studies and explore to what extent Green Chemistry can contribute to the objectives of the Convention, in particular chemical safety and security. In 2016, **OPCW** actively participated as a sponsor of the 6th International IUPAC Conference on Green Chemistry, including a self-organized session titled "Chemistry for a more Secure and Sustainable World: the OPCW's role."

IUPAC International Conferences on Green Chemistry (ICGCs)

Every two years since 2006, IUPAC, through the former Subcommittee on Green Chemistry, has promoted the International Conferences on Green Chemistry (ICGCs) series, a biennial event that continuously attracts several hundred scientists and technologists from academia, research institutes, and industries from all over the world. The aim is to exchange and disseminate new ideas, discoveries, and projects on green chemistry and sustainable development [13]. Following events in Dresden, Moscow, Ottawa, Foz do Iguaçu, and Durban, the biennial Green Chemistry Conferences traveled to Venice, Italy in Sep 2016 and, more recently, to Moscow, Russia in October 2017 (see report page 42). The series has become a cannot-miss event in the field. The 8th event is planned to be held in Bangkok, Thailand, in September 2018 (see greeniupac2018.com). The Chemical Society of Thailand, who will be hosting the conference, is developing a rich and attractive program under the theme "Green for Sustainable Growth: Chemistry, Scaling-Up, Economic, Regulation, Innovation, and Education". The conference will provide insight into recent developments in green chemistry, as well as a platform to exchange ideas, foster collaboration, and develop new partnerships for the future.

ICGCSD also supports the call for the CHEMRAWN VII Prize for Green Chemistry [14], which in recent years has been presented at the ICGC. The Prize of USD 5000 is granted to a young investigator (less than 45 years of age) from an emerging region who is actively contributing to research in Green Chemistry. The next nomination deadline is **31 March 2018**.

ICGCSD FOCUS on Education

A Postgraduate Summer School on Green Chemistry will be held in Venice 7-14 July 2018, hosted in the prestigious *Palazzo Ducale* (Doge's Palace) in Saint Mark's Square (see IUPAC project 2017-006-2-041 [15] or http://www.unive.it/greenss2018). The project follows 10 previous Summer Schools on Green Chemistry held in Venice from 1998 to 2008 [16] and aims to teach post-graduate students and post-doctoral researchers in chemistry from all over the world, from either academia or industry, how to approach pollution prevention from a chemical standpoint. About 80 students and 20 teachers will participate in the event. Main topics will be:

- Chemistry beyond chlorine
- New reaction pathways
- Exploitation of renewable resources; and, for the first time
- Green Chemistry for cultural heritage restoration

The School will offer scholarships to young talented chemists from either academia or industry from emerging countries not yet affiliated with IUPAC. These scholarships will facilitate a profitable and continuous exchange of ideas and information among the students, the instructors, and the different stakeholders, in particular members of IUPAC Divisions and Committees interested in Green Chemistry, for the establishment of long-lasting scientific relationships. Mixing Academia and Industry, ICGCSD will rely on cooperation among different stakeholders, including IUPAC Divisions and Committees as well as organizations such as UNESCO, ICSU, OPCW, OECD, *etc.* All stakeholders will be invited to participate in the Summer

School planning process and scientific sessions.

In 2019, inspired by the IUPAC Centenary Celebrations, the school will aim to teach Green Chemistry to young graduate and post-graduate chemists from all over the world, in particular to those from African countries. The School will be hosted by the Department of Chemistry at the University of Dar Es Salaam in Tanzania in May.

The PhosAgro/UNESCO/IUPAC partnership in Green Chemistry for Life has evolved as a Grant Programme that seeks to support talented young scientists aged 39 and under, offering research grants of up to US$30,000 to help them implement their innovative research projects for the advancement of green chemistry [17]. ICGCSD regularly participates in the Jury and in 2017 it met for two days in March to judge nominations. Other members of the Jury were Natalia Tarasova, IUPAC President, Nicole Moreau, former IUPAC President and now member of the Executive Committee of ICSU, and Sean Corish, former IUPAC Treasurer and Chair of the Jury, and Pietro Tundo. In 2017, 150 applications were received, an increase of 25 % on the previous award. This elevated number of applications clearly shows the success of the initiative, which has positive repercussions not only on the young scientists involved, but also on the networks that support the program financially. Six winners from a range of countries were selected and were officially awarded grants at the St. Petersburg International Economic Forum ("SPIEF") on 2 June 2017 [18]. The 5th call for green chemistry research projects on innovations in the processing and utilization of phosphogypsum is now open to young scientists until 28 February 2018.

ICGCSD and Industry

ICGCSD pays great attention to external industrial perspectives and priorities and seeks additional sponsorship and support from industrial sources for its work. To this end, one of ICGCSD's proposals is to establish an Industrial Green Chemistry Panel in order to open a dialogue on Green Chemistry and Sustainability with relevant international industries and related chemical organizations. This project fits well with the IUPAC mission. IUPAC, as an international body with the goal of bringing together academic and industrial chemists working together to address global issues, would be a suitably neutral body for such purposes. This would be a bottom-up approach, since IUPAC would provide the panel to which industries will be welcomed to make their voice heard.

The sharing of common objectives would help:

- Support and accelerate the achievement of sustainability goals in the chemical industrial context;
- Propose challenging R&D themes in green chemistry and green engineering;
- Qualify green chemistry and green engineering for responsible innovation in industry;
- Coordinate efforts in Industrial Ecology and Industrial Symbiosis; and
- Ensure the cross-fertilization of green solutions in different industrial contexts.

Epilogue

Green Chemistry is growing and is rapidly adopted worldwide. IUPAC, with the support of ICGCSD, has a well-defined role in it: not only to harmonize the many different requests coming from all around the world with IUPAC mission and expertise, but also because IUPAC aims to create a common language of chemistry and, therefore, to utilize this new terminology in Green Chemistry in a rigorous scientific manner and context.

How Much Green is Green?

There is a general desire for chemists to be green given modern global concerns of climate change and resource scarcity, but **there is a confusing multitude of meanings and approaches in the literature to green metrics and** both in organic and inorganic chemistry. ICGCSD has recently initiated a project on **Metrics for Green Syntheses** that will ultimately provide guidelines for dealing with metrics limitations and for publishing results.

See IUPAC project 2017-030-2-041 or Project Place p. 31 for details

References and Notes

1. Address by Irina Bokova, St Peterburg, 2 June 2017 http://unesdoc.unesco.org/images/0024/002497/249743e.pdf or in Russian, ibid ... 249743r.pdf
2. IUPAC Interdivisional Committee on Green Chemistry for Sustainable Development, https://iupac.org/body/041
3. IUPAC Strategic Plan https://iupac.org/who-we-are/strategic-plan/
4. P. T. Anastas and J. C. Warner. Green Chemistry: Theory and Practice. Oxford Science Publications, Oxford (1998).
5. *Pure and Applied Chemistry,* 2000, Vol. 72, No. 7, pp. 1207-1228 and the entire July 2000 issue
6. In 1998 IUPAC co-sponsored with OECD a Workshop on

Sustainable Chemistry that was held in Venice (report *Chem Int.* Jan 1999, Vol 21, No 1 pp 17-21; https://doi.org/10.1515/ci.1999.21.1.17c). Subsequently the outcomes of the workshop were approved at the OECD meeting in Paris, on 6 June 1999; see Series on Risk Management No. 10: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(99)19/PART1; ibid ... PART2 and PART3. For a review of the 7 principles, see PART3, p. 204.

7. https://sustainabledevelopment.un.org/TFM/STIForum2017/OnlineDiscussion
8. https://sustainabledevelopment.un.org/forum/?forum=88c
9. https://sustainabledevelopment.un.org/forum/?forum=89
10. http://www.unep.org/chemicalsandwaste/sustainable-chemistry-inputs-stakeholders
11. https://isc3.org/events/mainstreaming-sustainable-chemistry-launch-isc3-iscnet/?mo=5&yr=2017
12. https://www.opcw.org/events-calendar/event/2017/11/16/event/tx_cal_phpicalendar/call_for_nominations_for_a_workshop_on_green_and_sustainable_chemistry_in_the_context_of_the_chemical_weapons_convention
13. https://en.wikipedia.org/wiki/International_Conference_on_Green_Chemistry
14. https://iupac.org/2018-chemrawn-vii-prize-green-chemistry-call-nominations/
15. https://iupac.org/project/2017-006-2-041
16. http://www.incaweb.org/education/summer_school_on_green_chemistry and http://www.incaweb.org/education/ssgc.php
17. http://www.unesco.org/new/en/natural-sciences/science-technology/basic-sciences/chemistry/green-chemistry-for-life/
18. https://iupac.org/unesco-phosagro-iupac-award-joint-grants-spief-best-young-scientists/

Note 1: IGCG records in *Pure and Applied Chemistry* (PAC)

- ICGC-1, Dresden, Germany, 10-15 Sep 2006 | PAC 2007, 79(11), 1833–2105
- ICGC-2, Moscow, Russia, 14-20 Sep 2008 | PAC 2009, 81(11), 1961-2129
- ICGC-3, Ottawa, Canada, 15-18 Aug 2010 | PAC 2011, 83(7), 1343-1406
- ICGC-4, Foz do Iguaçu/PR, Brazil, 25-29 Aug 2012 | PAC 2013, 85(8), 1611–1710
- ICGC-5, Durban, South Africa 17-21 Aug 2014 | PAC 2016, see preface by L. Mammino, PAC 88(1-2), pp. 1-2, http://doi.org/10.1515/pac-2015-5009 and follow keyword 'Green Chemistry V' | report in *Chem Int* Jan 2015, p. 35
- ICGC-6, Venice, Italy 4-8 Sep 2016 | PAC 2018, 90(1 & 2) in press | report in *Chem Int* Jan 2017, p. 36

Pietro Tundo <tundop@unive.it> is a professor at the Università Ca' Foscari di Venezia (Italy) and the current chair of the Interdivisional Committee Green Chemistry for Sustainable Development. ORCID.org/0000-0002-8167-356X. Elena Griguol is a collaborator at the Università Cà Foscari di Venezia (Italy).

(continued from page 17)

on Sunday, 10 September. Apart from the scientific program, which included a one day ***Angewandte Chemie*** Symposium with prominent international speakers such as four Nobel Prize winners, several events for the public took place in Berlin. Another highlight was the introduction of the place where the DChG was founded 150 years ago into GDCh's Historic Chemical Landmarks Program, in which the GDCh honored in particular the achievements of its founding President August Wilhelm von Hofmann. The series of events was concluded with the symposium 'Experiment Future - Values Thinking in Chemistry,' in which the role of chemistry with regard to the future of education, nutrition, health, and sustainability was addressed with speakers from industry, academia, and NGOs such as the Organization for the Prohibition of Chemical Weapons. (Check chemistryviews.org for *GDCh Fact of the Month* www.chemistryviews.org/view/gdch150.html and *Highlight of the GDCh Jubilee Year 2017* www.chemistryviews.org/details/ezine/10643896/Highlight_of_the_GDCh_Jubilee_Year_2017.html)

Summary

With more than 30 000 members from academia, industry and other areas, the GDCh today represents a large, important and vibrant community of experts. Although most of the members have a chemistry background, everyone who supports the society's aims and goals and accepts GDCh's code of conduct is invited to join the German Chemical Society. The organization's history, the global network it is embedded in, and the high scientific and ethical standards form the foundation for future-oriented activities. This involves using the innovative power of chemistry to pursue a world that provides safe and environmentally benign energy, clean water, healthy and sufficient food, and medical support for all inhabitants of our planet.

Wolfram Koch <w.koch@gdch.de> is Executive Director of the Gesellschaft Deutscher Chemiker e.V. / German Chemical Society.

www.gdch.de