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Repositioning the chemical sciences for a sustainable future

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Summary

The chemical sciences face major challenges in the 21st century. Among these, internal challenges include how best to structure the teaching, research, applied interfaces and governance of a mature science in a highly competitive and rapidly changing world. Challenges related to the external environment include how to ensure the relevance of the chemical sciences, how to improve their sometimes tarnished image and reputation, and how to optimise their contribution to solving oncoming global problems. A group of scientists associated with the International Organization for Chemical Sciences in Development has been discussing and writing about these issues for several years and here summarise their published work to date. It is argued that chemistry needs repositioning to achieve its potential in sustainable development. The changes advocated are encapsulated in the concept of 'one-world chemistry'. One implication of this approach is that chemistry needs to embrace systems thinking, partly to improve understanding of the subject itself and partly as a way of developing a wider understanding of the interactions of the chemistry system with other systems. The group has commented on the need for the world of chemistry, including its professional associations at national and international levels, to undertake deep-seated reforms to reorient its thinking and practice. Emphasis has also been placed on the responsibility of individuals and professional associations to adopt and promote the approach of 'scientific temper'; to combat 'fake news'; to reform the deeply flawed word of science publishing which is damaging to the careers of scientists and to the advancement of science; and to give leadership in ensuring equity, diversity and inclusion.

1. Introduction

Chemistry is central to understanding the nature of all matter and to learning how to transform it. While those working in the field are well aware of this, among the public, policy makers, science funders and media there is often much less appreciation of the importance and value of the field. For more than two centuries, chemistry has made outstanding contributions both to the advancement of scientific knowledge and to the creation of products that have been the basis of wealth-generating industries, improved health and enhanced lifestyles [1]. Yet, periodic waves of unpopularity of the field among students and low ratings of the subject and its practitioners and industries among the public have been seen in recent decades – often associated with accidents such as chemical spillages or explosions, with instances of the misuse of chemical substances in warfare or creating drug addiction, or with pollution of the environment.

The International Organization for Chemical Sciences in Development (IOCD) was founded at UNESCO in 1981 and subsequently registered in Belgium as an international non governmental organization. Initially focused on using the chemical sciences to assist in development in low- and middle-income countries through education, research and capacity development of individuals and institutions, in recent years IOCD has directed its attention to the promotion of the chemical sciences as a core scientific discipline and as central to the achievement of sustainable development globally. Since 2014, a group of four scientists affiliated with IOCD has been meeting to discuss and write about these issues. Formalised under the name 'Chemists for Sustainability' (C4S), this IOCD core action group (Figure 1) and occasionally additional guest collaborators has so far produced around 20 articles. These have been published in diverse locations including leading chemistry and science journals, magazines, newspapers and websites, sometimes relayed in languages other than English and aimed at a wide range of audiences from science researchers, educators and administrators to the general public. The C4S group has argued that chemistry as a discipline needs redesign and reform, in order to ensure that it is attractive and productive as a science and relevant to solving 21st century challenges. This review summarises the work to date.

2. Repositioning chemistry for the 21st century

Early writings by the C4S group [2,3] acknowledged chemistry as a great enabler that, for two centuries, has played a key role in conquering diseases, solving energy problems, addressing environmental challenges, and providing discoveries that have underpinned new disciplines and spawned new industries. However, it was also recognised that, to meet the demands of the future, this mature science must expand into new frontiers, a move requiring broad support and necessitating that the public and policy-makers understand its pivotal role in every facet of life. Building trust and confidence, the essential bedrocks for long-term support, requires openly acknowledging not only chemistry's considerable achievements but also the problems and harms that have been caused, whether intentionally or not, by some chemical processes, products and wastes.

Figure 1. IOCD action group 'Chemists for Sustainability' meeting in Hyderabad in 2017. Left to right: Alain Krief, Henning Hopf, Stephen Matlin, Goverdhan Mehta

This early work identified several themes that would be picked up in subsequent articles. One of these was the importance of reforming chemistry education at all levels in order to make chemistry better understood, more relevant to contemporary issues and able to inspire future generation of chemists. A paper presented by a member of the C4S group at the 2016 Gordon Research Conference on 'Chemistry Education as an Agent in Global Progress' took to one of the leading fora of chemistry educators the challenge of achieving a chemistry literacy that is relevant to people's lives [4].

Another issue identified was that many of the field's major national and international associations require sweeping reforms to balance their focus on the professional advancement of their members with an active role in bolstering recognition, respect, and understanding for chemistry from the public. It was recognised that changing this balance would require breaking very long-standing traditions of many of these associations, and would need champions to step forward at both leadership and grassroots levels to press the case for reforms. Furthermore, it was emphasised that industry, as a critical constituent of the chemistry community, should do its part by wholeheartedly embracing ethical rules and practices and engaging in responsible chemicals management and responsible innovation. Industry needed to engage with consumers and have frank conversations with a society that demands transparency and has deep concern about risks. This could be supported by academia, working with industry to clearly explain the science, applications, and impacts and relating these to local contexts.

3. Chemistry for sustainable development

Our planet faces a myriad of substantial challenges in the 21st century and many of these were recognised in the Sustainable Development Goals (SDGs) adopted at a UN summit in September 2015 as part of the UN Agenda for Sustainable Development 2030 [5]. The earlier Millennium Development Goals had focused on particular problems of the world's poorest countries, to help overcome which the richer nations would provide aid. However, the new SDGs embrace a global vision of development for all, building on the core principle of sustainability and with responsibility to be shared by all countries according to their capacities.

The C4S group observed that chemistry can and must make pivotal contributions to help realize the ambitious UN Agenda for Sustainable Development, agenda, by developing the processes, products and monitoring mechanisms that the SDG goals and targets require. However, it cautioned that, to do so optimally, chemistry needs to undergo major changes in its priorities, approaches and practices [6,7]. To achieve chemistry's potential, there could not be business as usual, in education, research or practice and the chemical industry needed to fully embrace green chemistry, ethical rules and practices and engage in responsible innovation [8] and responsible chemicals management. The C4S group concluded that chemistry can re-imagine itself as a champion and driver of sustainable development, transforming its image from often being seen as the source of environmental pollution and degradation to being recognized as a core sustainability science – a key driver of practical, sustainable and ethical solutions to many of the world's greatest challenges in the 21st century. A redesign encompassing chemistry's image, approaches and practices was seen as desirable because the world needs chemistry's best endeavours to avert or mitigate the many global crises that are currently unfolding, and also because it will reinvigorate the entire field of chemistry and transform its appeal as an ethical science worthy of investment and esteem by society.

4. 'One-world chemistry' and systems thinking

The nature of the reforms necessary to reposition chemistry as a sustainability science were encapsulated by the C4S group in the concept of 'one-world chemistry' (OWC). This was presented [9-13] by the C4S group as a new orientation for the discipline.

OWC incorporates a number of basic principles. It emphasises the need for chemistry to be a science for the benefit of society, embracing the understanding that human health, animal health and the environment are all interconnected. It therefore requires developing awareness of how chemical systems interact with many other systems, including the physical, biological, and ecological systems of the planet. It recognizes that the solutions to many fundamental and applied problems traverse geographic and disciplinary boundaries and mandate cross-disciplinary approaches. Furthermore, it insists that chemistry must at all times be practiced in an ethical manner, taking account of the short- and long-term impacts of how it is conducted and of the uses, potential uses, and fates of its products and by-products.

Acting on the consequences of these principles requires embracing the mission of sustainability, the employment of systems thinking in relation to all aspects of the practice of chemistry, strengthening the capacity of chemistry for cross-disciplinary working, and improving the productivity of the interface between academia and industry.

The C4S group has repeatedly stressed the importance of enhancing the capacities of chemists for cross-disciplinary working. In the past, chemistry's evolution as a well-defined and separate academic discipline provided a secure base for research that added to fundamental knowledge and contributed to technological applications in chemical, biotechnology and materials industries. But the practice of science – and, in particular, the interaction between disciplines in order to share ideas, advance fields and tackle complex problems – is changing fundamentally in the globalized world of the 21st century. Cross-disciplinary engagements can take a number of different forms: they can be multidisciplinary (bringing together knowledge and problem-solving approaches from a host of fields that can each contribute, 'side-by-side', to different stages or aspects of problem-solving); interdisciplinary (developing expertise in working across the boundaries between chemistry and other disciplines and transferring methods from one discipline to another); or transdisciplinary (beyond interdisciplinary – which still implies the autonomy of subjects working in cooperation – creating a new synthesis of chemistry and other subjects in which knowledge, methods and solutions are developed holistically: recognizing that valuable knowledge can be found in the spaces between defined disciplines, addressing the complexity of problems and the diversity of perceptions of them). It has been argued [14] that the shift from disciplinary to transdisciplinary research corresponds to a transition from compartmentalized, corrective, problem solving approaches to systemic, preventive ones.

A system is an interconnected set of elements that is coherently organized in a way to achieve a function or purpose [15]. One definition of systems thinking, adapted from the Waters Foundation [16], is that it uses strategies to develop understanding of the interdependent components of dynamic systems. Another way of expressing this is that systems thinking is about seeing and understanding systems as wholes rather than as collections of parts. While little attention had hitherto been given to systems thinking in the chemistry domain, it has been a major factor in the development of other science and technology disciplines, including biology and engineering [17,18]. For chemistry, it offers opportunities not only to enhance learning by adopting a broader view that encourages experiential learning and purposeful reflection, but also to develop understanding of how the chemistry system interacts with the physical, biological and environmental systems in which it is located, as well as with human systems (e.g. economic, political, regulatory and social systems) within which chemistry is practiced and its processes and products used.

5. Systems thinking in chemistry education

Ideally, the development of a capacity for systems thinking should begin early in chemistry education, enabling the learner both to benefit from the broader understanding of the discipline that comes with seeing chemistry itself as a system; and to better appreciate how the chemistry system interacts with and impacts on the world as a whole.

In collaboration with Peter Mahaffy [19], the C4S group has set out the case for chemistry education to adopt systems thinking and begun examining pathways through which this can be achieved. A proposed framework (Figure 2) places the chemistry learner at the centre, interacting with three nodes or essential elements. The learner systems node explores and describes the processes at work for learners in general, while the chemistry teaching and learning node focuses on features of learning processes applied to the unique challenges of learning chemistry. The earth and societal systems node orients chemistry education toward meeting societal and environmental needs articulated in initiatives such as the SDGs and descriptions of the earth's planetary boundaries. Educational systems to address the interface of chemistry with earth and societal systems include green chemistry and sustainability education, and use tools such as life cycle analysis [20,21].

IOCD is currently collaborating with the International Union for Pure and Applied Chemistry (IUPAC) in a global project to develop learning objectives and strategies for infusing systems thinking into chemistry education, using the framework of the three nodes [22].

6. Reforming the role of chemistry organizations

Chemistry organizations should play a leading, pro-active role in the repositioning of chemistry that is required in the 21st century. The C4S group argues that this necessitates reforms in both national (e.g. chemistry societies) and international (e.g. IUPAC) bodies that represent the interests of the discipline and the profession [23,24].

At the national level there are more than 250 diverse chemistry organisations around the world, about quarter of which are national chemistry societies that have traditionally functioned in multiple roles, including as learned societies, voices of the chemistry profession and protectors of the interests of professionals and the public. In a changing environment, not all these bodies have responded effectively to the emerging challenges, such as sustainability, the need to develop

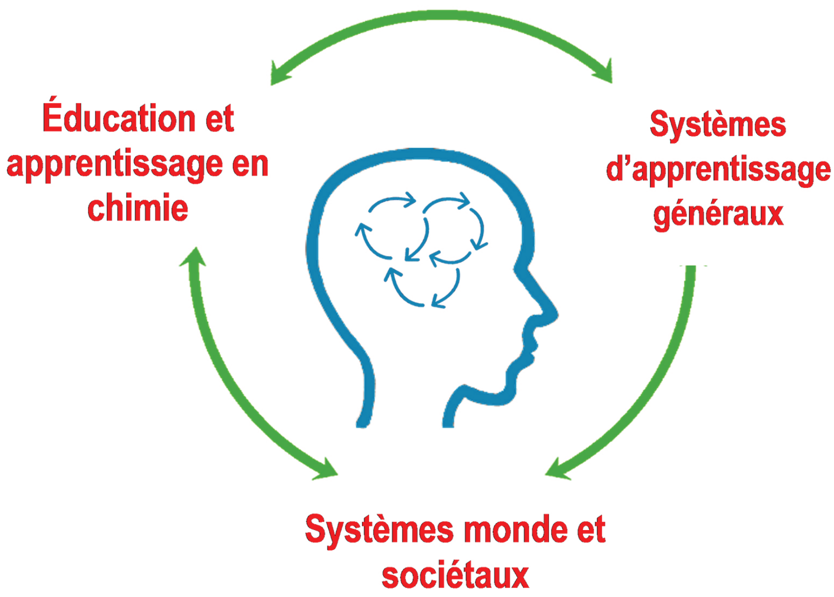

Figure 2. Framework for analysis of systems thinking in chemistry education

cross-disciplinary collaborations, or the active promotion of ethical behaviour, research integrity or equity, diversity and inclusion.

One major dilemma for chemistry organizations, including those representing chemistry at a national level and those focused on a particular sub-discipline or technique, is that many have become heavily dependent financially on the income they receive from publishing learned journals. Faced with the profound changes now taking place in the publishing world that are driven by the impact of rapidly evolving communications technologies (see also the section below on scientific publishing), there are threats to the sustainability of the organizations themselves as well as challenges to their representational and promotional roles on behalf of the discipline. The C4S group has advocated that the societies need to undertake a rebalancing of the priorities they give to publishing, compared with service to their membership and to the broader needs of the discipline and of society.

At the international level, chemistry organizations have often evolved as geographical or global federations of national chemical societies and industry associations, as well as of bodies that focus on a specific chemistry subject area, technique, process, or class of substance; or as new agents aiming to facilitate networking or the promotion of particular objectives. One especially important example is IUPAC, which was formally founded in 1919, includes many national chemical societies among its members and provides global networking opportunities through its diverse activities. Over time, a number of the international chemistry organizations have experienced stagnant or declining membership, stressed finances in an increasingly competitive environment, and outdated missions and archaic governance structures that no longer suit 21st century needs.

Considering how the diverse chemistry organization can adapt, in order to help lead and support the repositioning of the field as well as to ensure their own continued relevance and sustainability, led the C4S group to propose a menu of options for consideration. The menu includes a refreshing of the vision, mission, and organizational objectives and strategy; development of a clear, relevant international perspective; engagement in championing a refreshed chemistry education that is contemporary in its content, focus, and methodologies; a whole-hearted commitment to scientific publishing that is genuinely open access; development of models and strategies to restore and re-energise the academia/industry interface; a more active role in making the case to policy-makers, industry and the public for sustained, improved funding for the chemical sciences; submission to periodic, independent external evaluations to ensure good governance, fitness for purpose and effectiveness; and stronger engagement in actively promoting the value of the chemical sciences to diverse audiences in and beyond science.

7. Chemistry and health

Chemistry has made central contributions to improving health, wellbeing and life expectancy in the last two centuries, with both synthetic and analytical chemistry have played leading roles [25]. However, even greater contributions are needed now, when the world is experiencing a range of emerging and re-emerging infectious diseases, widespread resistance to antimicrobial agents, a growing global burden of non-communicable diseases and the impacts on health of a range of phenomena including planetary over-population, ageing societies, urbanization, environmental pollution and climate change.

Considering the interlocking systems of education, research, commercial development and regulation within which chemistry's contributions and impacts on health occur, the C4S group has identified a number of disconnections that are preventing the optimal contributions that the chemical sciences can make [26]. Interlinked systemic reforms are advocated, involving (1) re-contextualization of the chemistry/health interface through creating a recognized field of "the chemical sciences and health", which will strengthen teaching and research and prepare a body of chemical scientists trained in cross-disciplinary working and able to undertake systems approaches to multi-faceted, complex problems; (2) determined and comprehensive efforts, by countries wishing to retain or strengthen their pharmaceutical development capacities, to reinforce their education, research, and innovation eco-systems; and (3) adoption of an integrated approach to the regulation of pharmaceuticals, food, and the environment.

8. Championing chemistry

The C4S group has highlighted the need for new champions of chemistry to step forward to help drive the reforms that are required in the discipline, ensure its continuing relevance to contemporary challenges and attract broad-based support and recognition of the contributions it makes to global progress [27].

It is argued that attracting the required champions must begin with developing a clarity of purpose and of commitment to ethical behaviour and solving societal challenges, such as that exemplified in the OWC framework. With this essential pre-requisite in place, the response to the question 'where are the champions' is that everyone must become champions: individual chemists, academic departments in colleges and universities, chemistry societies, environmental advocacy groups, government agencies, and industry. They must act both individually and collectively through coordinated initiatives. Within this overall shared responsibility, championing can be given leadership and afforded stronger public appeal and greater impact by encouraging the emergence of role models and skilled advocates.

9. Science in the 'post-truth' era

An especially important challenge, not only to chemistry but to the entire field of science and beyond, has emerged in what has come to be known as the 'post-truth' era [28]. Throughout history, there have been examples of the denial of facts and of evidence-based conclusions, but in recent decades this has emerged as a powerful phenomenon affecting opinions and behaviour on an unprecedented scale. The deliberate dissemination of lies, misinformation and untrue propaganda, including about facts and interpretations of science, has been seen in relation to issues such as vaccination to prevent serious and fatal diseases, health consequences of particular lifestyles, environmental pollution and climate change, as well as in connection with broader societal issues of economics and politics. The result has been the distortion of behaviours, policy positions, voting choices and lifestyle decisions, with impacts at individual, community, national and global levels.

The C4S group has drawn attention to the need for scientists generally, including chemists, to actively oppose this 'post-truth' tendency, combatting its insidious effects through actively denouncing lies, presenting true facts in a clear and comprehensible way to the public and policy makers, and espousing and advocating for the practice of 'scientific temper' [29-31]. This term was coined by Nehru [32] in 1946 to describe a way of life that rejects anti-science thinking. It is an individual and social process of thinking and acting, which uses the scientific method and which may, consequently, include questioning, observing physical reality, testing, hypothesizing, analysing and communicating. 'Scientific temper' describes an attitude which involves the application of logic. Discussion, argument and analysis are vital parts of scientific temper. Elements of fairness, equality and democracy are built into it.
Scientists and science institutions urgently need to establish and ensure the provision of resources for strategies that will help to educate and communicate to the public and policy-makers the significance and implications of advances and discoveries in science that impact on society and the environment. These communications should always emphasise the rigour of the scientific method and the dependence of science facts and theories on evidence that is tested and validated.

For the longer term, strengthening respect for valid science and wariness of post-truth tactics requires building a greater level of science literacy in society, the media and policy-makers.

Scientists themselves must act as models of good practice, operate a zero-tolerance policy towards all attempts to disseminate falsified and exaggerated data.

10. Scientific publishing

The C4S group has analysed the system of scientific publishing, with emphasis on a perspective from the chemical sciences [33]. They described a deep crisis that is unfolding, in which the present, flawed model for scientific publishing is damaging not only to science but also to the careers of many scientists and to the reputation of the field of scientific publishing as an honest, ethical and respected endeavour.

The analysis indicates that the crisis is being driven by the conjunction of sub-systems that connect the primary purpose of science publishing – that of scientific advancement to ensure that discoveries and theories are widely disseminated and exposed to critical examination – with financial and reputational rewards. These rewards, which create conflicts of interest for both authors and publishers, lead to severe distortions in behaviour, sometimes amounting to unethical or dishonest practices. Moreover, the increasing tendency to use bibliometric data as a surrogate for quality and scientific value has further distorted the reward and reputational systems.

The C4S group has argued that piecemeal solutions are unlikely to be effective or sustainable and the time is ripe for the stakeholders in science publishing to seek new, systemic approaches. These must comprehensively address the fundamental flaws in a ways that genuinely serve the interests of science, scholars and society. The reformed system must ensure equitable opportunity for all researchers – without regard to their prior scientific reputation, location or gender – to make their findings public, gain credit for the quality of their contributions and have open access to all the published work of others; and it must provide a high level of assurance to scientists, policy makers and the public about the reliability of the information accessed.

The outlines of an action plan for the science community to generate such a process are suggested. Key elements of this include simultaneously addressing the three intersecting elements of the scientific publishing system:

- Financial system: The central question that needs to be answered is: who pays, and how much, to achieve the most equitable and open access that is sustainable? Efforts must be made to go beyond the 'gold' and 'green' models, which enable open access for readers but still provide very large profits for publishers and encourage predatory practices and the creation of fake journals. Efforts must be made to reform the over-burdened peer-reviewing system and to minimise the costs of organizing and managing publishing, with an emphasis on paper-free, electronic formats in open repositories. Ultimately, the lowest costs will be generated if publishing is managed efficiently by not-for-profit entities. The more that publication costs and consequent fees charged to authors or users can be reduced, the lower will be the barriers to publication and access and the less will be the attractiveness to operators of predatory and fraudulent journals. There needs to be a serious debate, led by science academies and professional organizations and engaging scientists, policy makers, industry, science funders and foundations, about the best way to move open access forward sustainably. The European Union's new open science initiative points to a promising avenue for development [34].
- Science advancement system: There is mounting evidence that the traditional peer reviewing system is no longer able to function effectively. There have been – and continue to be – massive increases in the number of papers being published, while the refereeing process itself is no longer reliable, since many examples are beginning to emerge where reviewers have failed to detect false data. There is also an increasing lack of confidence due to non-transparency and evidence of biases in the system and of randomness in outcomes. New models of review by peers are being explored and

are beginning to demonstrate the potential for reform, including review by groups of scientists on the web, in either fully open or semi-structured modes. These approaches can be ongoing, adding perspective to the correctness and value of the work over time. Further examination of these models and development of a universal approach is needed, through the joint effort of scientists, their institutions, archive centres and research funders. Whatever new system emerges, the integrity and fairness of decision-making needs to be robustly ensured through the rigorous application of scrutiny, adjudication and sanctions. Scientists who deliberately distort or falsify data must face penalties that are well defined, publicized and rigorously enforced, so that the public and policy-makers, as well as scientists, have confidence in system. This will require that science publishing is subjected to rigorous scrutiny that is independent of the scientists' institutions and the publishers.

- Reputational system: Current practices in the evaluation of scientific merit place excessive emphasis on metrics of publication numbers, the citation rates of papers and the status of the journals in which they appear. These metrics drive many of the worst features of the present scientific publishing system. In particular, they are used inappropriately for evaluating the extent of authors' contributions to the field and for judgements about career advancement, rather than employing qualitative judgements based on expert assessment. The San Francisco Declaration on Research Assessment (DORA) emphasizes that funders and institutions should acknowledge that *"the scientific content of a paper is much more important than publication metrics or the identity of the journal in which it was published"* and that publishers should *"greatly reduce emphasis on the journal impact factor as a promotional tool"* [35]. However, a more extensive initiative is now needed, which eradicates the use of all publication metrics for evaluations of authors' scientific contributions and the use of 'impact factors' as an indicator of journal quality. Academic institutions, funding agencies and bodies representing professional scientists should engage to generate a 'DORA 2' and to vigorously promote its universal application.

11. The chemical sciences and equality, diversity and inclusion

While the human right of all people to be treated fairly and without discrimination is enshrined in the UN's Universal Declaration [36], in practice many individuals and groups around the world suffer prejudice, exclusion and sometimes abuse and physical violence. The campaign to achieve equity, diversity and inclusion (EDI) in all areas has been gathering momentum around the world in recent years. The science community needs to be very actively engaged in this movement – not only to ensure that it is stamping out bad practices and ensuring EDI within its own institutions and practices, but also because progress in EDI will play an increasingly important role in advancing science itself, through the inputs made by the inclusion of individuals with more diverse backgrounds, experiences and perspectives, who will contribute to maximising innovation and creativity in science for the benefit of humanity [37,38]. It will enhance the capacity of science to tackle global problems and help achieve the SDGs and will help to create "a shared future in a fractured world [39].

In collaboration with Vivian Yam [40], the C4S group has discussed the challenge of dealing with conscious or unconscious forms of bias and discrimination in the sciences and argues that the chemical sciences can play a leading role in addressing biases, through (1) becoming a model of good systemic practice in policies, processes and actions; (2) developing practical skills through training in cultural competence; and (3) promoting a stronger evidence base, to uncover both the extent of problems and the degree to which approaches to improve equality, diversity and inclusion are working [41,42].

Conclusion

What began as a concern that chemistry urgently needed to undertake a repositioning to refresh both its internal dynamism and external image has become an evolving, detailed picture of the comprehensive nature of the reforms required.

Central themes that have emerged include the importance of a broader approach to education and practice in which greater emphasis is placed on cross-disciplinary approaches, systems thinking and the positioning of chemistry as a sustainability science and, overall, a science for the benefit of society. Applications of systems thinking to several facets of the science and societal milieus in which the chemical sciences operate have led to calls for specific and wide-ranging reforms in chemistry education, research and practice in general; as well as for major reforms in relation to areas such as chemistry and health, scientific publishing and the pursuit of equity, diversity and inclusion.
It is stressed that achievement of these reforms requires effort by all actors involved in the chemical sciences, including the educators, researchers, practitioners and professional bodies and associations at national and international levels. It will be necessary to tackle uncomfortable positions and vested interests to achieve the reforms. The prize will be the evolution of the next phase of this important science, generating increasing public confidence, support and understanding for its principles, processes, objectives and appreciation of its valuable capacities and products.

Biographical Sketches

Prof. Stephen Matlin is a former Professor in Biological Chemistry at the City University, London and Warwick University in the UK and a former Executive Director of the Global Forum for Health Research in Geneva. He is currently an Adjunct Professor in the Institute of Global Health Innovation at Imperial College London and Senior Fellow in the Global Health Centre at the Graduate Institute, Geneva. He is a member of the General Assembly and Head of Strategic Development at the International Organization for Chemical Sciences in Development.

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Prof Alain Krief is a French and Tunisian citizen. He is a former President of the Société Royale de Chimie (Belgium) and Director of the Laboratory of Organic Chemistry at the University Notre Dame de la Paix in Namur, Belgium and subsequently an Emeritus Professor there. He is a visiting Professor in the Hussain Ebrahim Jamal Research Institute of Chemistry, University of Karachi, Karachi,Pakistan. Since 2010 he has held the position of Executive Director of the International Organization for Chemical Sciences in Development.

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