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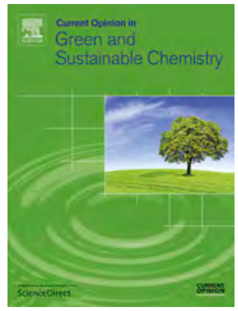

Green Chemistry Education and Activity in China

Mei-Yan Wang, Xiao-Ya Li, Liang-Nian He

PII: S2452-2236(18)30047-6

DOI: 10.1016/j.cogsc.2018.07.001

Reference: COGSC 193

To appear in: *Current Opinion in Green and Sustainable Chemistry*

Received Date: 17 April 2018

Accepted Date: 3 July 2018

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Mei-Yan Wang,[a,b] Xiao-Ya Li[a] and Liang-Nian He*,[a]

[a] State Key Laboratory and Institute of Elemento-Organic Chemistry, College of Chemistry, Nankai University, Tianjin 300071, P R China

[b] Collaborative Innovation Center of Chemical Science and Engineering, Tianjin University, Tianjin 300072, P R China

Corresponding author: Liang-Nian He, (heln@nankai.edu.cn)

Highlights

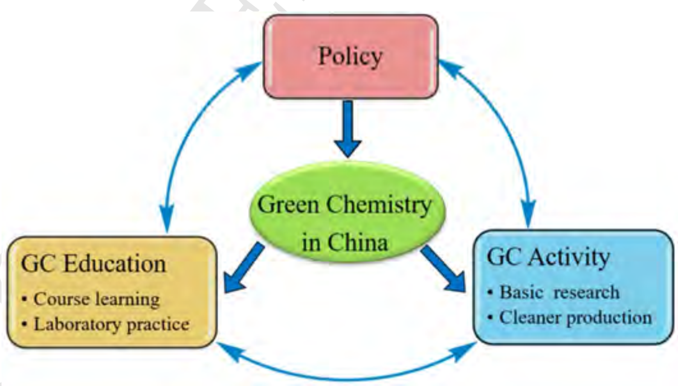
• Two models on green chemistry development in China, i.e. green chemistry education and green chemistry activities, is presented.

• The current status and tendency of green chemistry in China is elaborated.

• The policy support for green chemistry is deemed to be positive in China.

With the increase of global environmental pollution, green chemistry has been an inevitable trend in the development of chemistry and chemical engineering, thus attracting much attention from the academia to industry and to governments. As a response to the "green challenge", the so-called green chemistry movement has spread all over the world. In this perspective, we would like to present main programs associated with green chemistry in China, with a focus on green chemistry education and related activities.

Graphical abstract



Introduction

In 1987, the World Commission on Environment and Development first proposed the concept of "Sustainable Development" which was widely recognized by the international community. In this case, the emergence of green chemistry became a general trend in the field of chemistry and chemical engineering. Over the next three decades, there is a strong international commitment to green chemistry education [1-11]. Being influenced by the worldwide boom of "green chemistry", the China Central Government became aware of the importance of green chemistry and considered the development of green chemistry as a major component and driving force of social development. In 1990, the "China Sustainable Development Strategy Report" was proposed by the Chinese Academy of Sciences to reduce the destruction by the traditional extensive economy model to the ecological environment. Subsequently, the report of the 17th National Congress of the Communist Party of China (CPC) formally pointed out a "Scientific Outlook on Development". In May 1997, the 72nd Xiangshan Science Conference [12] was held with the theme of "The Challenge of Sustainable Development to Science – Green Chemistry", which was the first time the concept of green chemistry was pointed out in China. Since then, the development of green chemistry has achieved an explosive growth both in industry and academia. The rapid development of green chemistry can hardly happen without publicity, education, policy, etc. In this article, we aim to present the latest progress on green chemistry education and activities in China, according to the frameworks as summarized in Figure 1.

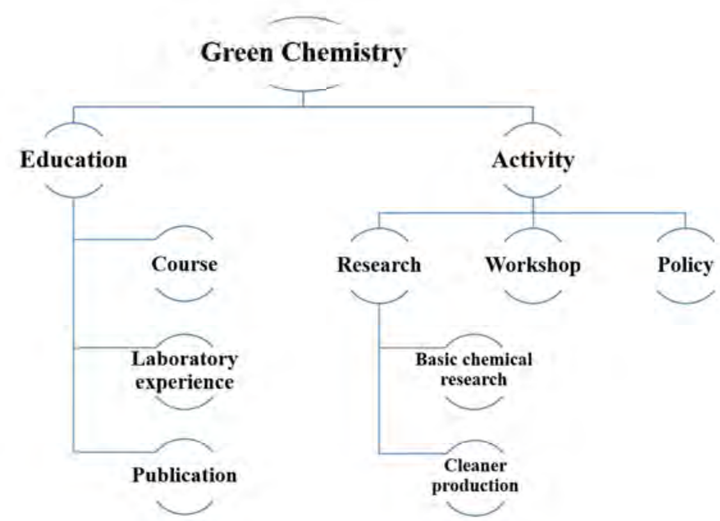


Figure 1. Frameworks for the development of green chemistry in China

Green chemistry education

For the last several decades, many students, not only in China but also around the world, have been faced in chemistry education with issues such as coping with the hole in the ozone layer, keeping water resources clean, and searching for both renewable sources of energy and raw materials. Hence, adding green and sustainability issues to the chemistry curricula or developing systematic green chemistry education is irresistible. On the other hand, green chemistry education is considered the cornerstone of green chemistry development. Therefore, it constitutes one of the most innovative and challenging tasks in chemistry worldwide. Green chemistry education aims at incorporating information about green chemistry into chemical education, thus being called to design suitable options for all the broad educational areas – curriculum development, teaching, learning and outreach, from in-class activities to laboratory experiments to the dissemination of information to the public. At present, China's green chemistry education keeps pace with the international development. Typically, a large number of green chemistry courses have been opened in universities and colleges. Diverse publications also come out.

(1) Green chemistry courses

The practice of green chemistry involves optimizing for versatile goals and desired outcomes. To provide students some experiences in making such decisions, green chemistry concepts have been introduced to a number of courses [6,13,14]. In 1998, The University of Science and Technology of China first established the Green Chemistry Center to carry out studies on biomass conversion. Meanwhile, Green Chemistry is introduced into the course schedules of academic degree and graduate education. This course is compulsory for those students majoring in chemistry or chemistry and materials. At the same year, Sichuan University established a doctoral program in green chemistry, aiming to foster sustainable scientific literacy and to develop corresponding skills among the graduate students in chemistry. E.g. a green chemistry course lectured was rated as one of the National Excellent Courses and the English version of this course has been included in the National "11th Five-Years Plan", indicating the recognition of Chinese government to green chemistry education. In addition, numerous Chinese universities and colleges have put out their courses related to green chemistry in the platform of Chinese Quality Open Courseware freely [15]. For instance, in the open course of "Green Chemistry and Sustainable Development" was supported and approved by the Ministry of Education of China summarizing the development and perspectives of green chemistry. The public class of "Green Chemical Technology" offered by Hebei University of Technology highlights green chemicals, the clean oxidation process of hydrocarbon and the chemical utilization of biomass glycerin, supercritical fluids and ionic liquids. All of these courses are designed to publicize the twelve principles of green chemistry, cultivate the correct perspectives of people to the relationships between chemistry, environment and human society, and finally inform the public to establish scientific outlook on social development.

(2) Laboratory experience

To a great extent, green chemistry is an experimental science. A meaningful way to teach and learn green chemistry is in a laboratory setting because most undergraduates remember an experiment much better than a lecture. In order to comply with the requirements of the green experiment, some changes in laboratory practice, such as reductions of scale, experimental improvements and the increased use of computer simulations, have been carried out [16-18].

In many laboratories, experiments for training students are shifted from the macro- to the micro-scale. In micro-experiments, the amount of reagents is far less than in conventional experiments, thus the resultant pollutants will be naturally decreased. By learning how chemistry research and chemical industry attempt to minimize the use of resources, maximize the effects, and protect the environment, students are able to recognize the significance of green education. In some developed countries e.g. the United State, Germany, Switzerland, the miniaturization of experiments has been quite widespread. In China, the miniaturization of experiments is under way. As an important aspect of green chemistry teaching, the miniaturization of experiments is receiving attention not only in higher education but also in primary and secondary education. On the other hand, dangerous substances are being replaced gradually by less poisonous alternatives. For instance, to handle the experiment of spontaneous combustion, white phosphorus usually has been used. White phosphorus is very poisonous, and the combustion of white phosphorus finally produces high-polluting phosphorus pentoxide, which is inconsistent with the principles of green chemistry. As a green alternative, magnesium silicide was introduced to the experiment of spontaneous combustion in experimental chemical courses. The hydrolysis of magnesium silicate can produce SiH_4, which can directly undergo the spontaneous combustion on water. The whole process generates no toxic substances or contaminants.

In addition to the various reagents used during the chemical experiments, great attention should be also payed to the pollution by experimental waste. In most laboratories, the waste is required to be classified according to their characteristic and to be collected into corresponding acid, base, volatile organic compounds (VOCs) or other containers. Especially for the VOCs, most of them can be separated and purified by distillation or membrane separation. In general, the potential of green experiments is not only to avoid pollution but also to strengthen students and teachers' environmental awareness. Therefore, how to perform green experiments has become a significant component of green chemistry education.

(3) Publications

The number of scientific publications with the key word ‘‘green chemistry’’ has increased substantially during the last several years. Excellent journals including, but not limited to *Green Chem.*, *ChemSusChem*, *Energy Environ. Sci.*, *Chem. Educ. Res. Pract.*, *ACS Sustain. Chem. Eng.* and *Org. Process Res. Dev.* are subscribed by most college libraries. The students, lecturers or researchers can acquire the latest news or strategies about green chemistry easily and timely. Several articles in *Green Chem.* [19-21] and *Chem. Educ. Res. Pract.*[22-24] also specifically deal with green chemistry education worldwide, which have referential significance to China. In addition, the research made by Chinese chemists and published in the leading journals of green chemistry is on the rise. Statistically, the articles published in *Green Chem.* contributed by Chinese chemists in 2017 account for 33.65% of the total (Fig. 2) [25], reflecting the tremendous development of green chemistry activities in China.

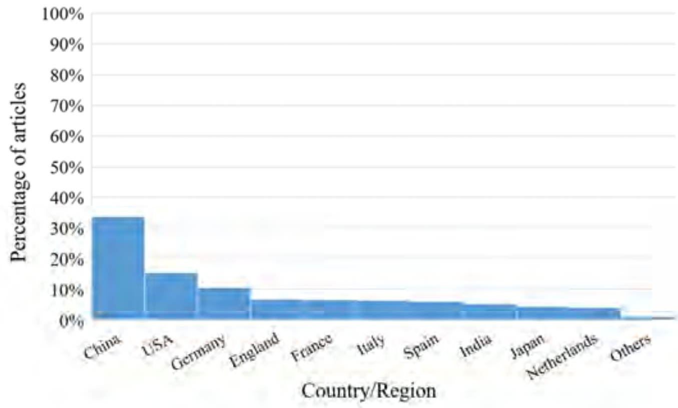


Figure 2. Percentage of articles in *Green Chem.* contributed by various country/region in 2017

Except for research papers, books are other media to spread the knowledge of green chemistry. For instance, a book by Hu et al. in China has compiled the *Principles and Application of Green Chemistry* [26], which systematically introduces the basic principles and method of chemistry and emphasis on the green application in products, raw materials, and processes. Another book by Yan has summarized the basic principles of green chemistry, green catalysis, biomass utilization, etc., and has emphatically introduced the application of green solvents in chemical synthesis in the book *Green Chemistry* [27]. It became a reference book for teachers, undergraduate students and researchers in chemistry and other relevant profession. The capture and utilization of carbon dioxide is one of green chemistry contents. In this field, the book *Carbon Dioxide Chemistry* [28] systematically introduces catalytic methodologies, fundamental principles, and updated advances with future trends in carbon dioxide utilization from the perspective of carbon dioxide activation principles, catalyst design, strategies for carbon dioxide conversion, reaction mechanisms, and industrial applications. This book is valuable for professional researchers in the areas of chemistry, chemical engineering, resources, and environment. It is also a good reference for undergraduate students to support green chemistry courses. From the point of resources preservation and environment protection, Zhang illustrated the green technology of organic synthesis, green chemical engineering, chemical process intensification, and the environmental governance in the book *Environment and Green Chemistry* [29], which is not only appropriate for undergraduate students but also accessible for the public. The soon-to-be published book series on *Green Chemistry Frontier* systematically analyzes and summarizes basic scientific theory and industrial applications of green chemistry, whereby it provides systematic references for scientific research in green chemistry and related fields. At the same time, the books can serve as bridges between fundamental research and practical applications to strengthen the implementation of green chemistry in industry.

All in all, the publications are helpful for readers to cultivate environmental consciousness, establish green chemistry ideas, and improve scientific literacy.

Green chemistry activities

(1) Research activities

In recent workshops in China, most of the topics discussed about green chemistry focus on either novel basic research, e.g. carbon dioxide utilization, green chemical routes, photochemical synthesis and bio-catalysis, or environmentally friendly chemical engineering, such as green technology, novel process strategies, or process intensification. Therefore, in this section, two types of research activities are described around the principles of green chemistry. One is focus on basic chemical research, aiming at making chemical synthesis more eco-friendly. Whereas, the other is oriented towards cleaner production, which emphasizes the harmony of economy and ecology.

a) Basic chemical research

Green basic chemical practice focuses on research and education with the purpose of creating more environmentally friendly ways for chemical synthesis and lays the foundation for the achievement of cleaner production. The exploration and development of innovation science and technology involving green chemistry principles are numerous [30-35] and a detailed discussion case by case is not possible. However, main progresses that reflect the trends of green chemistry in China are listed as below:

• Value-added consumptive/fixation uses for CO_2 at high volume.

• Biomass conversion to fuels and chemicals.

• Design of plastics and polymers that can be degraded innocuously.

• Design of recyclable/reusable materials.

• Less energy-intensive manufacture of photovoltaic cells.

• Development of non-material intensive energy sources.

• Development of surfaces and materials that are durable and do not require coatings and cleaners.

• Development of novel synthetic methodologies that is atom economical and benign to human health and the environment.

b) Cleaner production

Cleaner production is typically regarded as a way to achieve industrial ecology. The object of cleaner production is primarily on the corporate level. Except for manufacturing, processing, and formulation steps, green chemistry concepts and principles can also be applied to the other stages in product manufacturing (e.g., materials acquisition and input; packaging and distribution; product use; recycling, reuse and disposal). Based on basic green chemistry research, more and more green chemical processes are applied to industry. Among them, the production technology of carbon dioxide based polycarbonate is advanced in the world. In the aspect of chemical production using non-petroleum feedstock, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, has developed the technology of methanol to olefin (DMTO) with independent intellectual property rights. DMTO provides a new route for olefin production, which has driven the industrial development of over 30 million tons of methanol. The employment of green chemical technology to industrial production is the most effective strategy to solve the sharp contradiction between economic growth and environmental protection. In other words, it is an inevitable choice for the sustainable development of the chemical industry in China. The trend of green chemical engineering will mainly focus on three aspects. Firstly, it stresses the importance to promote structural reform of supply, facilitate the elimination of obsolete production capacities and overcapacities, and advances industry's faster upgrading. Secondly, biotechnology will become the dominant technology of chemical production because biotechnology has the advantages of high selectivity, low cost and low secondary pollution. Thirdly, micro-chemical engineering and technology is the common foundation and key technology of chemical engineering in the 21st century which will enhance chemical process safety, promote process intensification and miniaturization of chemical systems, increase the efficiency of energy and resource utilization, and finally achieve the purpose of energy conservation and consumption reduction. Guided by green science, technology and innovations, the government aims to advance the integration of green initiatives with innovation as the locomotive to realize cleaner production from raw materials to products.

(2) Green chemistry workshops

Various conferences and workshops on green chemistry greatly promote the development of green chemistry in China. Except for the Xiangshan Science Conference mentioned above, the International Symposium on Green Chemistry launched by the University of Science and Technology of China united with the international green chemistry organization has been one of the world's most influential conferences. In 2015, the International Conference on Green Chemistry and Technology which was first held in Guilin, Guangxi province, has been dedicated to creating a platform for exchanging the frontiers of research and sharing advanced methods of green chemistry and technology. To press ahead with the green "Belt and Road Initiative", the Belt and Road international green chemical high-end forums on the theme "Frontier and Opportunity of Green Chemistry, Sustainable Development of Chemistry" was held in July, 2017. This workshop launched a lively discussion around the development of sustainable materials, green chemistry and chemical engineering, green synthetic routes, and the opportunity and strategy for China's green chemistry development. The aim of all of the workshops is to provide an international platform to enhance exchange and cooperation in green and sustainable chemistry. It also lays a solid foundation for ensuring China's long-term development of green chemistry.

(3) Policy activities

The development of green chemistry is one of the central ways for the sustainable development of the chemical industry in China. For a long time, the government has put the development of green chemistry and industrial application on a more important and strategic position, and made a series of major deployments in decisions and foundations, especially in clean and efficient utilization of coal including CCUS (carbon capture, utilization and storage). Based on the deployments, a batch of MOE (Ministry of Education) Key Laboratories or Strategic Alliances have been set up, such as MOE Key Laboratory for Green Chemistry & Technology (Sichuan university), Green Chemical Technology (Tianjin university), Green Chemical Media & Reactions (Henan Normal University), National & Local Joint Engineering Research Center of Carbon Capture and Storage Technology (Northwest University), CTSA-CCUS (China Technology Strategic Alliance for CCUS Technology Innovation), etc.

In 2015, the fifth plenary session of the 18th CPC Central Committee put "green" development into the five major development ideas in the 13th five-year plan [36], which provides the policy support for green chemistry development. In the period of the "13th five-year", the government will mainly support cleaner production, promote the establishment of a low-carbon and circular development industry system, and advance industry's faster upgrading of technology and equipment. In the recent report delivered at the 19th CPC National Congress in October 18, 2017, General Secretary Xi Jinping deployed the green development mode from the aspects of promoting green development, solving prominent environmental problems, intensifying the protection of ecosystem and reforming the environmental regulation system, to speed up reform of the system for developing an ecological society [37].

Perspectives

In this article, we have presented two models on green chemistry development in China, i.e. green chemistry education and green chemistry activities, respectively. The two models have given an overview on the status of green chemistry in academia, public, enterprises and government. Hopefully, this overview will be of use for researchers, practitioners, companies and regulators who try to become better oriented in this field, not least as future paths are decided.

We would like to complete the article with a few words about different drivers and barriers for the implementation of green chemistry in China: The drivers can be divided into the following three categories: (1) policy pull, (2) market pull/public relations, and (3) science and technology push. Similarly, the barriers may be also divided in three categories: (1) knowledge/technological barriers, (2) culture/communication barriers, and (3) economic barriers.

Green chemistry has been playing an important role in the sustainable development of China including efficient utilization of resources, environmental protection, renewable energy development, etc. Aiming at being a trustworthy and responsible country, China is taking an active part in the green chemistry movement. With policy support, green chemistry can be carried out more smoothly and practically in China. Predictably, the trends of green chemistry in China will mainly focus on three levels in the future. Firstly, it is the basis to enhance green chemistry thinking and philosophy in the public by popularizing green chemistry education from primary school to university, from students to public, from the developed areas to less-developed regions. In this process, the theories, methods and applications should be updated timely to fit the rapid development of green chemistry. Secondly, China's total investment in basic green chemistry research such as the CO_2 capture and utilization, efficient catalysis, biomass utilization, photoelectric translation, green synthetic reaction, etc. will grow rapidly in coming years since policy orientation is supportive. Finally, it is irresistible to facilitate the elimination of obsolete production capacities and overcapacities and to advance industry's faster upgrading, especially in the pollution-intensive industries.

Acknowledgements

This work was financially supported by the National Program on Key Research Project (2016YFA0602900), National Natural Science Foundation of China (21472103, 21672119, 21421001).

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