УДК 378.4

ПРЕПОДАВАНИЕ ЗЕЛЕНОЙ ХИМИИ: ВЗГЛЯД ИЗ БЕЛАРУСИ ЧЕРЕЗ ПРИЗМУ МИРОВЫХ ТЕНДЕНЦИЙ

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Представлен анализ учебных программ по дисциплинам «зеленая химия» и «химия устойчивого развития», преподаваемых в различных университетах мира. Описаны тенденции развития образования и науки в области зеленой химии, а также актуальные проблемы преподавания зеленой химии, требующие решения. Исходя из полученных данных были выделены три подхода к построению траектории преподавания базовых основ зеленой химии: британский, европейский и американский. Первый подход предполагает углубленное изучение зеленой химии и формирование компетенций в этой области, второй подход – включение зеленой химии в традиционные химические дисциплины (органическую химию, аналитическую химию и др.), третий подход – включение зеленой химии в качестве раздела в такие практико-ориентированные дисциплины, как биотехнология, пищевая

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безопасность, экология и др. Рассматриваются содержание лабораторных занятий в программах по зеленой химии и применение метрики «зеленая звезда» (green star) для оценки их безопасности. Предлагается объединить усилия разных стран для продвижения и трансфера идей зеленой химии за счет создания центров передового опыта по использованию принципов и методов зеленой химии в научных исследованиях и образовательном процессе.

Ключевые слова: зеленая химия; химия устойчивого развития; учебные программы; безопасные лабораторные работы; центры передового опыта.

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GREEN CHEMISTRY TEACHING: BELARUSIAN VIEW THROUGH WORLD TENDENCIES

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The disciplines curricula on green chemistry and sustainable chemistry available in various universities of the world were analysed. Trends in education development and science in this particular area were described as well as actual green chemistry teaching problems that need to be solved. Analysing the data obtained three approaches defining a trajectory for teaching the basic foundations of green chemistry were identified: British, European, and American. The first one involves in-depth study and the formation of competencies in the field of green chemistry. The second approach implies the inclusion of green chemistry in traditional chemical disciplines (organic, analytical chemistry, etc.). The third approach implies the inclusion of green chemistry as a module in such practice-oriented disciplines as biotechnology, food safety, ecology, etc. The content of the laboratory classes in green chemistry curricula and the usage of a green chemistry metric «green star» for assessment of their safety are discussed. It is proposed to join efforts of different countries for green chemistry ideas promotion and transfer the green chemistry ideas through creation of green chemistry centers of excellence for the use of its principles and methods in scientific research and the educational process.

Keywords: green chemistry; sustainable chemistry; curricula; safe laboratory classes; centers of excellence.

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Introduction

Formed in the late 1990s green chemistry (GC) [1–4] has become today one of the leading scientific paradigms underlying the development of modern industrial production not only in the chemical industry, but also in other industries that use chemicals, for example, in the textile and food industries. However, the results of the survey allow us to state that the implementation of the principles of GC in a number of enterprises took place regardless of awareness of the leadership about this new scientific direction [5–7]. In their turn, many researchers including younger ones have no detailed information and deep understanding of GC concept [8, p. 16420]. This *status quo* needs to enhance the quality of high education in chemistry by the development of GC component. Numerous articles mirror the state of the art in GC education [9–10]. The most fundamental of them give the analysis on the difference between meaning of GC and sustainable chemistry (SC) and stress that it is needed «to mainstream GCE and SCE into chemistry and other education curricula and teaching, including gathering and disseminating best practice and forging new and strengthened partnerships at the national, regional and global level» [8, p. 16420]. There is the identification of suitable pedagogical approaches to teaching and learning GC [11, p. 7] to foster and improve scientific literacy in sustainability and to develop the corresponding skills among the present and future generations. However, most authors provide analysis only for individual countries or make the comparative analysis for several countries [10, p. 288]. This study was guided by the analysis of the programs of higher education institutions around the world, to reveal some trends in the development of GC in the field of education and identified advantages of some curricula that can be implemented in the educational system of the new-comer countries which are at the intention level or at the early beginning on the way to GC education.

Materials and methods

The most data analysed were obtained using the Internet resources. In particular, official web-sites of the universities, faculties, scientific departments. The well-known resources such as American Chemical Society (ACS) and Royal Society of Chemistry were used to search the curricula of the universities. These web-sites are connected with many scientific databases of the American and the British higher education institutions. The web-sites of the following universities were considered in the review (table 1).

Table 1

The list of considered universities

Country	University
Australia	University of Sydney
Austria	University of Vienna TU Wien University of Natural Resources and Life Sciences
Belarus	Belarusian State University
Brazil	University of Sao Paulo
Canada	Queen's University McGill University
China	Lanzhou Institute of Chemical Physics
Czechia	University of Chemistry and Technology Prague
Denmark	University of Copenhagen
Finland	Lappeenranta – Lahti University of Technology
Germany	Leuphana University Lüneburg
Ireland	University College Dublin
Japan	Shizuoka University
New Zeland	Aukland University
Norway	Western Norway University of Applied Sciences
Poland	Jagiellonian University University of Wrocław
Portugal	University of Aveiro NOVA University Lisbon University of Porto
Russia	Lomonosov Moscow State University ITMO University Mendeleev University of Chemical Technology
Singapore	National University of Singapore
Slovenia	University of Nova Gorica
Spain	University of Zaragoza
Sweden	Lund University

Ending table 1

Country	University
United Kingdom	University of York University of Nottingham
USA	University of Michigan – Flint George Washington University South Dakota School of Mines and Technology University of Massachusetts Boston Washington College Yale University Colorado School of Mines Hendrix College University of Florida St. Olaf College University of Scranton University of Wisconsin – Parkside
Vietnam	Hanoi University of Industry

We take into consideration the fact that some information cannot be up to date if some web-sites are not updated. According to the ACS, at least in the USA green chemistry programs are present in various formats in the universities of more than a half of the states. Thus, the main principle of universities selection was to encompass different geographical regions.

The authors used the following criteria for the comparative analysis: what higher education level includes a GC course or program in the curriculum, availability of GC laboratory classes, separation of GC into a special discipline or teaching the related disciplines along with it, and green research activity at the university.

Results and discussion

A number of programs of higher education institutions around the world has been analysed, some trends in the development of GC in the field of education and identified advantages of some curricula that can be implemented in the educational system of the Republic of Belarus have been revealed. The analysed countries are presented in the world map constructed by the authors (fig. 1).

Figure 1 represents the countries where GC is included in the universities curricula. The designed by authors map on fig. 2 reflects the spreading of GC courses in geographical manner.

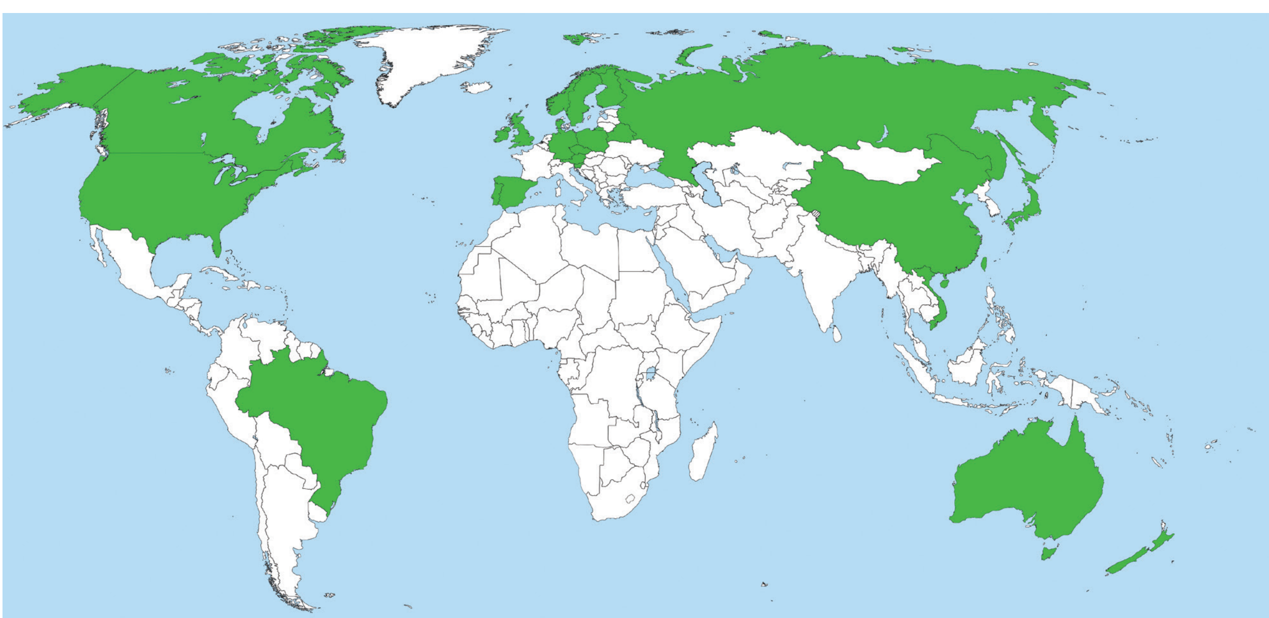

Fig. 1. Countries selected for the analysis according to the availability of data about GC education

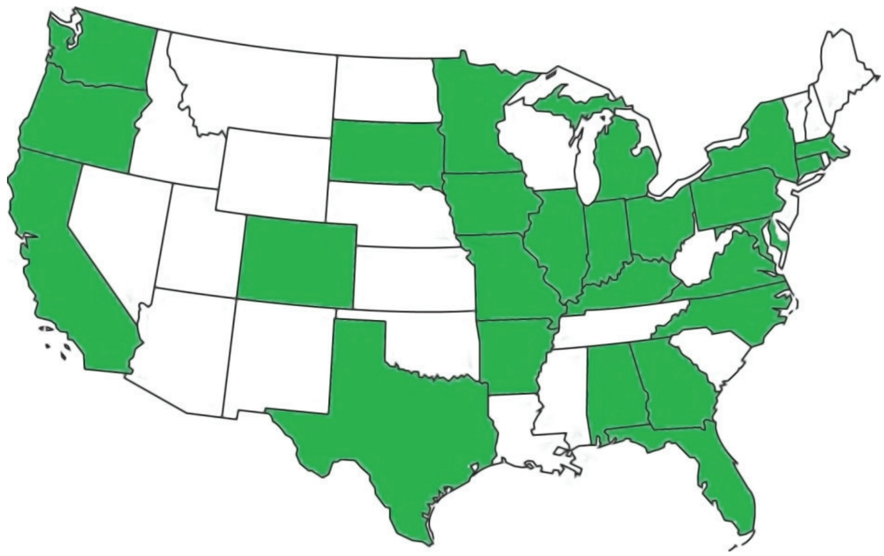

Fig. 2. American states, where GC presents
at the universities' curricula (according ACS)

Tables 2–4 illustrate the criteria for curricula analysing: the higher education levels (bachelor, master, PhD) where GC courses are taught (see table 2), the programs content (see table 3) and presence/absence of the laboratory classes (see table 4). It is pertinent to note that even the associate of science degree in GC is proposed. An associate degree is an undergraduate degree awarded after a course of post-secondary study lasting two or three years. It is a level of qualification above a high school diploma but below a bachelor's degree. The associate of science degree mainly applies in the United Kingdom and the USA.

As the data of table 2 illustrate, GC and related courses introduction into the curricula at all education levels is an exception not a rule.

The analysis revealed that both specialists and people who are far from chemistry often use the terms «green chemistry» and «sustainable chemistry» interchangeably, although these terms are not the same. The terms «green chemistry» and «sustainable chemistry» are similar in meaning, because they both focus on protecting our planet and its natural resources, but this is the only similarity.

Nowadays the blurring borders of the GC concept are an acute problem. The authors [12, p. 69] offer to attach to GC only those chemical processes, which fulfill all the twelve principles, but not one or two of them. This proposition can be expanded on educational programs.

Sustainable chemistry comes out for ensuring environmentally friendly development while GC focuses on the development, production and use of chemicals and chemical processes that minimise potential pollution or environmental risks and are economically and technologically feasible. Table 3 shows how various universities tackle this issue.

For example, the jointly hosted program of the University of Aveiro, the NOVA University Lisbon and the University of Porto «PhD in sustainable chemistry» includes such disciplines as new synthesis strategies, new catalysts design that belong to the field of GC. In addition, within the framework of the program, students study food safety, which is not related directly to GC, but clearly corresponds to the concept of sustainable development. They also study analytical transfer methods (hyphenated analytical techniques) and chemical biology. These two disciplines can be considered as tools of green chemistry (GC-tools) actively used by green chemists.

It should be noted that both SC and GC pursue sustainable development goals. At the same time, SC includes such areas as human health, environmental monitoring and food safety. In addition, SC strives for resource efficiency. The Organisation for Economic Cooperation and Development gives the following definition to SC: sustainable chemistry is a scientific concept aimed at improving the resource use efficiency to meet human needs for chemical products and services.

It is significant that in July 2019 even US congressional panel examined two concepts for differentiating between GC and SC: one well-defined with history and the other never and less distinct. It was told that the term «sustainable chemistry» has been introduced more recently and possesses countless definitions put forth by individuals, companies, trade associations, not-for-profit organisations, and governmental entities. In addition, there is no consensus on how to measure the sustainability of chemical processes and products. But the participants of the discussion emphasised that GC is an essential component of SC. Sustainable chemistry cannot be conducted in the absence of GC. Green chemistry according to IUPAC definition is the invention, design and application of chemical products and processes to reduce or to eliminate the use of hazardous substances for workers and consumers.

Table 2

The examples of the universities offering GC programs at different levels

Bachelor courses	Master courses	PhD courses	Several levels of education	Level of GC program is not concretised
• Lund University	• University of Copenhagen	• Jointly hosted program of the University of Aveiro, the NOVA University Lisbon, the University of Porto	• Aukland University	• Lanzhou Institute of Chemical Physics
• University of Nova Gorica	• Lomonosov Moscow State University	• Center for Green Chemistry of the University of Massachusetts Boston	• University of Sydney	• Shizuoka University
• University of Michigan – Flint	• University of Zaragoza		• National University of Singapore	• McGill University
• Hanoi University of Industry	• University of Nottingham		• Queen's University	• University of Sao Paulo
• Western Norway University of Applied Sciences	• George Washington University		• Washington College	• Lappeenranta – Lahti University of Technology
	• South Dakota School of Mines and Technology (*intent to plan*)		• Belarusian State University	• Center for Green Chemistry and Green Engineering of the Yale University
	• Leuphana University Lüneburg (*sustainable chemistry*)		• Mendeleev University of Chemical Technology	• Colorado School of Mines (*incorporated into bachelor of science curriculum*)
	• ITMO University (*chemistry of applied materials*)		• Jagiellonian University	• Toad Suck Institute for Green Organic Chemistry of the Hendrix College (*incorporated into bachelor of science curriculum*)
	• University College Dublin		• University of Wrocław	• University of Florida • (*incorporated into organic labs*)
	• Jointly hosted program of the University of Vienna, the TU Wien, the University of Natural Resources and Life Sciences		• University of York	• St. Olaf College (*incorporated into bachelor of science curriculum*)
	• University of Chemistry and Technology Prague			• University of Scranton (*incorporated into bachelor of science curriculum*)

Table 3

Program content at various universities in the world

University	Level of degree program
GC	
University of Nova Gorica	2nd, 3rd year of bachelor courses as an elective subject
Aukland University	Master course: introduction to green chemistry PhD course: contemporary green chemistry Postgraduate course: advanced green chemistry
University of Sydney	Green chemistry and renewable energy
Belarusian State University	Bachelor course: introduction to green chemistry Master course: green technologies in chemical industry
Hanoi University of Industry	Bachelor course: green chemistry
University of Wisconsin – Parkside	Associate of science degree: green chemistry
University of Massachusetts Boston	Center for Green Chemistry
University of Michigan – Flint	Bachelor course: green chemistry
Yale University	Center for Green Chemistry and Green Engineering
Jointly hosted program of the University of Vienna, the TU Wien, the University of Natural Resources and Life Sciences	Master course: green chemistry
Western Norway University of Applied Sciences	Bachelor course: green chemistry
University of Wrocław	Bachelor course: green chemistry Master course: catalysis and green chemistry
University of Chemistry and Technology Prague	1st year of master courses as a mandatory subject
SC	
Jointly hosted program of the University of Aveiro, the NOVA University Lisbon, the University of Porto	PhD program: sustainable chemistry
Lomonosov Moscow State University	Chemistry for sustainable development
Leuphana University Lüneburg	Master course: sustainable chemistry
Jagiellonian University	Bachelor and master courses: sustainable chemistry
GC + SC	
University of Nottingham	Master course: green and sustainable chemistry
University of Copenhagen	Master course: green and sustainable chemistry
National University of Singapore	Bachelor and master courses: sustainable and green chemistry
Washington College	Undergraduate course: green and sustainable chemistry
Mendeleev University of Chemical Technology	Department: green chemistry for sustainable development
University College Dublin	Undergraduate course: chemistry with environmental and sustainable chemistry
GC + N, SC + N	
Lund University	Bachelor course: green chemisrty and biotechnology
University of York	Bachelor and master courses, PhD program: green chemisrty and sustainable industrial technology
Queen's University	Bachelor course: environmental and green chemistry
George Washington University	Master course: interdisciplinary program
ITMO University	PhD program: chemistry of applied materials, sustainable chemical technologies

Note. *N* is a number of some disciplines, added to GC.

This uncertainty was reflected in the content of the curriculum. For example, such disciplines as air pollution and health, atmospheric chemistry of the environment, protein structure and functions, reactions and synthesis in medical chemistry are included in the program «GC and SC» of the University of Copenhagen. These disciplines are more related to chemical ecology, environmental chemistry and human health in general, while the GC and SC program at the University of Nottingham aims at providing students with classical competencies in the field of GC.

In general, analysis of the curricula shows that the boundary line between the notions of GC and SC is still uncertain. Moreover, there is a tendency to include in GC programs the disciplines that complement GC and are aimed at achieving sustainable development. This trend can be represented by the GC + *N* formula, when some disciplines (*N* is their number) are added to GC. For example, the program «Green chemistry and biotechnology» of the Lund University presupposes that students also acquire knowledge in the field of biotechnology. This combination is understandable, since today biotechnologies play an important role in the mineral processing industry, for example, in isolation of chemicals from plant materials by enzymatic methods. It is also important that biocatalysis has many attractive features in the context of GC: mild reaction conditions (physiological pH and temperature), environmentally compatible catalysts and solvent (often water) combined with high activities, and chemo-, regio- and stereoselectivities in multifunctional molecules [13, p. 1]. It will certainly upgrade the professional competencies of Lund University graduates. However, the question is whether or not to use this combination in the name of the program. The program «Sustainable and green chemistry»of the National University of Singapore also includes biotechnology. In addition to biotechnology, chemical technology is yet another popular component of *N* in the GC + *N* formula. In the United Kingdom, which can be considered as the founder of GC, the University of York program is called «GC and sustainable industrial technology». In our opinion, introduction of both biotechnology and chemical technology into GC courses as separate subjects is discussable because it is difficult to imagine GC itself without these technologies. Queen's University offers the program «Environmental and green chemistry», while George Washington University focuses on the program that includes not only GC, but also environmental chemistry, public health, politics and business. Thus, there is a tendency to replace green chemistry by GC + *N* or, at least, GC + SC.

At the same time, some additional disciplines such as photochemistry, toxicology, in-process analysis and others not directly related to the field of GC are not always indicated in the title of the program though quite often they form a part of it. A good command of these disciplines certainly plays an important role in GC application and therefore they should be part of GC-tools.

Sometimes GC programs are not highly specialised and include general chemical disciplines: organic, inorganic, physical, analytical chemistry. Presence of general and special chemical disciplines, together with GC, makes it possible to train generalists who are able to work in various branches of chemistry and put the acquired knowledge into practice. Extending the concept of GC to other fields of chemical sciences enhances the interdisciplinary character of GC programs.

Special attention should be paid to the development of GC in Germany, namely its sustainable initiatives such as DECHEMA (Society for Chemical Engineering and Biotechnology) presupposing close cooperation of industry, institutes, universities and government agencies. It is aimed at developing green metrics for chemical and biotechnological processes and green solvents for catalysis. Abiding by this interdisciplinary approach the German Chemical Society established a subject division on environmental chemistry and ecotoxicology. Federal Environmental Agency, Federal Ministry of Education and Research exercise strong support for GC initiatives in Germany. Besides, German Federal Environmental Foundation (the largest environmental foundation in Europe) encourages environmental protection projects of young researchers by personal scholarships. The network of six universities developing a new organic chemistry curriculum to teach students to apply GC in their research is another important project of this organisation.

As a result, we extracted three approaches to the construction of GC programs. Despite of the fact that GC programs are implemented all around the world the teaching technologies are differ. The article [10, p. 288] aims at comparing the programs by the following criteria: logic, objective and content. We would like to consider the criteria of content more profound.

The principles of programs elaboration were also identified in the course of analysis. It is our opinion that there are three approaches to GC programs design: separative, integrative and inclusive. We informally call them British, European and American approaches to stress their wide-spreading in the universities of these geographical areas. The British approach is a classic, conservative one. Within the framework of this approach, elaborated programs do not overstep GC boundaries and suggest its in-depth study. The programs of the University of Nottingham and the University of York testify to this fact. The program «Introduction to green chemistry» of the Belarusian State University also reflects the British approach. One of the advantages of the British approach is its focus on the economic aspect. Future specialists study to develop green chemical processes and promote economic benefits of safer processes. Students also undergo practical training based on the demands of private companies. Some American institutions of higher education pursue the same goals.

The European approach fits well with the GC + *N* formula. This approach is to some extent opposite to the British one. It presupposes introduction of additional disciplines related to GC and SC and considered as GC-tools. A similar approach is being implemented at the Lund University, where biotechnology is included in the program. The University of Copenhagen and the Portuguese program «PhD in sustainable chemistry» can also be included in this group, since the students of these universities study the disciplines related to sustainable development as a whole. At the same time, the program of the University of York, called «GC and sustainable industrial technology» formally corresponds to the GC + *N* formula but adheres to «pure» GC and doesn't contain such optional disciplines as food safety or air pollution and health which can be found in the program of the University of Copenhagen and in the Portuguese program «PhD in sustainable chemistry».

The American approach does not run counter to the British and European ones, it compliments them. This approach provides both elaboration of a separate GC program and integration of this discipline into other programs. There are many universities in the USA that have separate high-quality GC programs, but there are also other programs where GC is an important integral part of the curriculum. Hendrix College in Arkansas, Colorado School of Mines, University of Florida in Gainesville, St. Olaf College in Minnesota, and University of Scranton in Pennsylvania have such programs. The recent example of GC incorporation is the general chemistry course redesign at the University of Berkley [14, p. 2410]. One may notice that GC is often introduced directly into organic synthesis programs. It is logical enough taking into account the specifics of this area. To some extent, the American approach is correlated with the European one, where additional disciplines are included in the GC program. Under the American approach, GC is introduced into other programs.

The question whether it is better to design a brand-new, stand-alone course, or try and add greener modules to existing courses in the curriculum has been discussed many times. The pedagogical literature shows that these two approaches can be successful, but there are obvious «pros and cons». In both cases, this strategy allows young specialists to enhance their competence [15, p. 1].

It can be assumed that in the near future the identified approaches will be combined into the general one. Integration of the approaches will upgrade interdisciplinary communication and promote synergies in learning. In its turn, this will help to enhance the competence of specialists making them clearly understand the whole picture of the chemical world and developing their ability to apply knowledge from various fields of chemistry for sustainable development.

Table 4 reflects the laboratory classes in the GC programs. Currently the issue of teaching laboratories safety is one of the main priorities of GC development.

However, the fact is that the concept of safety is quite broad. In this regard, it's very important to create green metrics to evaluate the greenness of chemical processes and to compare them. The elaboration of green metrics is one of the main fields of GC development. They range from classical and simple ones such as atom-economy and E-factor to modern and complex metrics [16, p. 18]. For example, carbon efficiency, effective mass yield, mass intensity, process mass intensity, reaction mass efficiency are used in organic chemistry. NEMI labeling is taken into service in green analytical chemistry [17, p. 10928]. Green aspiration level, green hazop analysis, green motion et cetera quantify the environmental impact of producing the specific pharmaceutical agents in pharmaceutical industry [18, p. 752]. The stay of the art in GC metrics usage is the only beginning of the way but we will move from metrics for the assessment of the efficiency of chemical reactions in organic synthesis to metrics for the assessment of the sustainability of different processes for the production of basic chemicals in the biorefinery.

But now when facing the metrics for evaluation of teaching laboratory experiments it makes sense to use a holistic GC metric as described in the educational letter «Green star» [13, p. 1]: «The basic idea of green star is to construct a star with a number of corners equal to the number of principles used for the evaluation of the synthesis reaction, all 12 or only some if the remaining are not applicable, each corner with length proportional to the degree of accomplishment of the corresponding principle – a semi-quantitative view of the global greenness of the reaction can then be obtained by looking at the star and appreciating its area: the larger the area, the greener is the reaction».

It may be premature to talk about criteria of greenness while the very existence of laboratory classes is a problem in GC programs that focus not on general chemical disciplines but on GC itself.

The problem of GC-curriculum content was in detail described by E. Jarvis in her research letter «Green chemistry in United States science policy». She noted that general and organic chemistry courses are often «fairly narrowly defined in scope of creative content» and they often assign a modest role to GC by attaching it to elective courses. Therefore, not all the students acquire relevant knowledge in the field of this discipline.

Special attention has to be paid to the lack financial investment to GC innovations. It happens due to the fact that GC importance is often underestimated (the results of these innovations are not seen right away, but in long-term perspective the costs fully pay off and insure stable income). One of the main ways to solve the problem is to raise awareness among business persons and policymakers in order to foster the fastest law adoption and to attract investments. It can be reached via drawing up legislation, holding hearings or interacting with executive agencies and highlighting the role that lobbyists can serve to set the stage for suggesting a GC student project in a lecture or lab course. According to the author, namely the students have a good potential as this «lobbying force». This idea can be applied to solve the issue of GC specific labs absence in the curricula [19, p. 161].

Table 4

GC programs with laboratory classes at the universities in the world

GC programs are present	GC programs are absent or not mentioned	Labotary classes are not connected with GC directly
• Jointly hosted program of the University of Aveiro, the NOVA University Lisbon, the University of Porto • University of Nottingham • University of York • George Washington University • Washington College • University of Michigan – Flint • Center for Green Chemistry of the University of Massachusetts Boston • ITMO University (*chemistry of applied materials*) • Leuphana University Lüneburg (*sustainable chemistry*) • University of Wisconsin – Parkside (*green chemistry*) • Yale University (*Center for Green Chemistry and Green Engineering*) • Jointly hosted program of the University of Vienna, the TU Wien, the University of Natural Resources and Life Sciences • Western Norway University of Applied Sciences	• University of Zaragoza • University of Sydney • Lanzhou Institute of Chemical Physics • Shizuoka University • National University of Singapore • Queen’s University • McGill University • Lomonosov Moscow State University • Belarusian State University • Hanoi University of Industry • University College Dublin • Colorado School of Mines • University of Sao Paulo • Hendrix College • University of Florida • St. Olaf College • University of Scranton • University of Chemistry and Technology Prague	• Lund University (*biotechnology practicum*) • Lappeenranta – Lahti University of Technology (*technology practicum using cleaner and more energy efficient method*) • Mendeleev University of Chemical Technology • Jagiellonian University • University of Wrocław

A good tool to introduce GC into the laboratory practice is to use the visualisation procedure. Visualisation of chemistry climate change (VC3) approach is described in details in the article [20, p. 1027]. It gives the possibility to apply «inert» knowledge into rich context using case studies and context-based learning methods. Thus, it fosters better understanding of GC practical importance.

Table 4 shows that not all university programs contain such laboratory classes, even though they ensure high-level theoretical training and university based research.

For example, at the Belarusian State University a theoretical course is being taught only. In 2012 it received an international status because of established cooperation with lecturers from Slovakia, Poland, Czechia and Hungary within the framework of the International Visegrad Fund project, but laboratory classes are still being elaborated. One of the problems is the high cost of the equipment used by green chemists for synthesis and it takes time to create well-equipped laboratories. An additional point to emphasise is that Belarusian State University is a leader in Belarus in developing of innovative green technologies [21, p. 1]. For example, a green process for hydrated cellulose fibers production has been developed. Nowadays in most countries these fibers are produced using viscose technology, which is hazardous for the environment. As an alternative to non-biodegradable synthetic plastic, the Belarusian State University has developed edible films for packaging foodstuffs. At present the joint project of the Belarusian State University and the Institute for Tropical Technology of Vietnam Academy of Science and Technology aimed at the production of nanocomposite films and coatings with biocidal properties based on natural polymers is going. Both these technologies will be the basis for the creation on new methodologically unique laboratory experiments for developing students' research skills. However, if we take into account the university's 4G strategy, it is necessary sharing experiences on GC at enterprises and integrating it into lectures for students at the universities. The program jointly organised by the Vietnam Chemicals Agency (Ministry of Industry and Trade), the United Nations Development Program and Hanoi University of Industry demonstrates the example of such an activity.

We also hope to create the Belarusian National Center for GC Experience Exchange (Belarus Green Chemistry Excellence Center, GCEC-Belarus) at the Belarusian State University, for strengthening the Belarusian State University image in the international arena as a national leader in the field of green technologies. This center will facilitate exchange of best practices between specialists in the field of green innovations in the chemical industry and ensure GC education development. It will result in improving the quality of chemical education and in training highly qualified specialists.

However, GC curriculum should not limit itself only to laboratory classes. It can also include other practice oriented activities, for example, to fulfill various projects in the form of cooperative learning, to consider particular chemical reactions and technologies, to analyse them from the GC standpoint and to suggest their improvement. Students need to design part or all of the procedure in the form of inquiry. Teacher chooses archetypal experiment and then requires students to design the special procedure for it [22, p. 2845]. One can find the descriptions of a case study in GC course design, mini-research projects experiment and others in the article [23, p. 29].

Conclusion

As a result of the comparative analysis of GC programs at the universities around the world, a number of trends in teaching this discipline can be identified.

1. At present, the most common approach is not to focus directly on GC teaching, but on the formula GC + N or GC + SC.

2. Quite often programs contain the term SC in their title sand include the ecological aspects and sustainable development goals that go beyond the scope of GC.

3. As for the programs content, three main approaches to their elaboration can be identified: separative (British), integrative (European) and inclusive (American) which attach different role and place to GC in the programs.

4. GC programs are often accompanied by general chemical disciplines and other subjects that can act as discipline-tools (GC-tools).

5. One of the main problems of GC introduction into the university curriculum is lack of laboratory classes even though the educational institutions ensure high-level theoretical training and high level university-based research. We propose to join the efforts of different countries for promoting GC ideas by introducing mandatory laboratory classes into the GC courses. Taking into account that young generation is the generation of the Internet it will be a sound strategy to use simulators of chemical laboratory based on augmented and virtual reality in addition to traditional practical labs. Augmented and virtual reality chemistry laboratories are a tool for carrying out chemical experiments in a safe, simulated environment. It enables users to observe and study various chemical reactions created by him or her as well as other users. This software provides an ability to run everything from simple chemical experiments for students to complex experiments involving new substances creation with dozens of interconnected stages utilising varying reactants and equipment. Such laboratories allow us to take care of natural resources, to save reagents in the learning process, to reduce the environmental burden and to make chemistry education safe.

References

1. Cathcart C. Green chemistry in the Emerald isle. *Chemistry and Industry*. 1990;21:684–687.
2. Drašar P. Green chemistry – dream or reality (minimum impact chemistry). *Chemicke Listy*. 1991;85(11):1144–1149.
3. Campbell A. Green chemistry. *Chemische Berichte.* 1992;28(7):652.
4. Morgan JM. An earth system science approach to global environmental chemistry education: an overview. *ACS Symposium Series*. 1992;483:457.

5. Anastas PT, Warner JC. *Green chemistry: theory and practice.* New York: Oxford University Press; 1998. 14 p.
6. Erythropel HC, Zimmerman JB, de Winter TM, Petitjean L, Melnikov F, Lam CH, et al. The Green ChemisTREE: 20 years after taking root with the 12 principles. *Green Chemistry*. 2018;20(9):1929–1961. DOI: 10.1039/C8GC00482J.
7. Tarasova NP, Makarova AS, Vavilov SYu, Varlamova SN, Shchukina MYu. Green chemistry and the Russian industry. *Herald of the Russian Academy of Sciences*. 2013;83(6):499–505. DOI: 10.1134/S1019331613060117.
8. Kummerer C. Sustainable chemistry: a future guiding principle. *Angewandte Chemie. International Edition*. 2017;56(52): 16420–16421. DOI: 10.1002/anie.201709949.
9. Dichiarante V, Ravelli D, Albini A. Green chemistry: state of the art through an analysis of the literature. *Green Chemistry Letters and Reviews*. 2010;3(2):105–113. DOI: 10.1080/17518250903583698.
10. Bodlalo LH, Sabbaghan M, Jome SM. A comparative study in green chemistry education curriculum in America and China. *Procedia – Social and Behavioral Sciences*. 2013;90:288–292.
11. Chen M, Jeronen E, Wang A. What lies behind teaching and learning green chemistry to promote sustainability education? A literature review. *International Journal of Environmental Research and Public Health*. 2012;17(21):7876. DOI: 10.3390/ijerph17217876.
12. Andraos J, Dicks AP. Green chemistry teaching in higher education: a review of effective practices. *Chemistry Education Research and Practice*. 2012;13(2):69–79. DOI: 10.1039/C1RP90065J.
13. Ribeiro BD, Marrucho I, Gonçalves L, Coelho MAZ. Biotechnology and green chemistry. *BioMed Research International*. 2014;2014:590586. DOI: 10.1155/2014/590586.
14. Armstrong LB, Rivas MC, Zhou Z, Irie LM, Kerstiens GA, Robak MT, et al. Developing a green chemistry focused general chemistry laboratory curriculum: what do students understand and value about green chemistry? *Journal of Chemical Education.* 2019;96(11):2410–2419. DOI: 10.1021/acs.jchemed.9b00277.
15. Kolopajlo L. Green chemistry pedagogy. *Physical Sciences Reviews*. 2017;2(2):20160076. DOI: 10.1515/psr-2016-0076.
16. Sheldon RA. The E factor 25 years on: the rise of green chemistry and sustainability. *Green Chemistry*. 2017;19(1):18–43. DOI: 10.1039/C6GC02157C.
17. Tobiszewski M, Marć M, Gałuszka A. Namieśnik J. Green chemistry metrics with special reference to green analytical chemistry. *Molecules*. 2015;20(6):10928–10946. DOI: 10.3390/molecules200610928.
18. Roschangar F, Sheldon RA, Senanayake CH. Overcoming barriers to green chemistry in the pharmaceutical industry – the Green Aspiration Level™ concept. *Green Chemistry*. 2015;17(2):752–768. DOI: 10.1039/C4GC01563K.
19. Jarvis E. Green chemistry in United States science policy. *Green Chemistry Letters and Reviews*. 2019;12(2):161–167. DOI: 10.1080/17518253.2019.1609599.
20. Mahaffy PG, Holme TA, Martin-Visscher L, Martin BE, Versprille A, Kirchhoff M, et al. Beyond inert ideas to teaching general chemistry from rich contexts: visualizing the chemistry of climate change (VC3). *Journal of Chemical Education*. 2017;94(8): 1027–1035. DOI: 10.1021/acs.jchemed.6b01009.
21. Grinshpan D, Savitskaya T, Tsygankova N, Makarevich S, Kimlenka I, Ivashkevich O. Good real world example of wood-based sustainable chemistry. *Sustainable Chemistry and Pharmacy*. 2017;5:1–13. DOI: 10.1016/j.scp.2016.11.001.
22. Płotka-Wasylka J, Kurowska-Susdorf A, Sajid M, de la Guardia M, Namieśnik J, Tobiszewski M. Green chemistry in higher education: state of the art, challenges, and future trends. *ChemSusChem*. 2018;11(17):2845–2858. DOI: 10.1002/cssc.201801109.
23. Dicks AP, Bastin LD. *Integrating green and sustainable chemistry principles into education*. Elsevier: Oxford; 2019. 255 p.

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