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# Green Chemistry in Higher Education: State of the art, challenges and future trends

--Manuscript Draft--

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| **Manuscript Number:** | cssc.201801109R1 |
| **Article Type:** | Review |
| **Corresponding Author:** | Justyna Małgorzata Płotka-Wasylka<br>Gdansk University of Technology<br>Gdansk, POLAND |
| **Corresponding Author E-Mail:** | plotkajustyna@gmail.com |
| **Order of Authors (with Contributor Roles):** | Justyna Małgorzata Płotka-Wasylka |
| | Aleksandra Kurowska-Susdorf |
| | Muhammad Sajid |
| | Miguel de la Guardia |
| | Jacek Namieśnik |
| | Marek Tobiszewski |
| **Keywords:** | green chemistry * education * teaching methods * green chemistry metrics * educational tools |
| **Manuscript Classifications:** | Green chemistry; Sustainable Chemistry |
| **Abstract:** | Nowadays, there is an increasing interest on world sustainability in our societies and, because of that, university students would like to know how human actions affect the health status of our planet. This is mainly due to their basic knowledge of such problems as global warming and greenhouse gases. Students would like to gain the knowledge how to safeguard the Earth for future generations. This must involve changes in education programs at interested institutions and universities. To ensure that the future chemist generation is equipped with the proper knowledge, significant efforts would be needed. Thus, this article aims to present the history of green chemistry and its milestones and also to give ideas how to teach this subject. Discussion on awareness in the field of green chemistry as well as on existing materials for teaching is presented. In addition, green chemistry metrics, which should be known and used by professors and students, are described. Teaching methods of green chemistry are also given, paying special attention to organic and analytical chemistry education. |
| **Response to Reviewers:** | The authors would like to express their sincere gratitude to Reviewers whose positive attitude and constructive comments contributed to the improvement of the manuscript. We are even more happy with your constructive criticism. Thank you very much for your time devoted to reviewing our manuscript and for detailed comments. We are glad that the overall opinion about the manuscript is positive. We tried to response all the comments pointed out by the Reviewers and applied all suggested changes.<br>Below you can find our responses to the specific comments. All the changes made in the manuscript are marked in yellow.<br><br>Reviewer 1<br>A very important book not cited by the authors which discusses all of the topics in their paper is given below:<br>Worldwide Trends in Green Chemistry Education, (V. Zuin, L. Mammino, eds.), Royal Society of Chemistry, 2015. (addresses many of the educational concerns raised by the<br>authors)<br>The reference has been cited.<br><br>An important topic missing from the discussion of green metrics (Section 3.3) is the importance of balancing chemical equations that links reaction mechanism, identifying reaction by-products, and quantifying waste production. This is the very first step that needs to be done before any metrics evaluation can be carried out. Leading references |

that describe the importance of this are as follows that should be cited:
J. Andraos*, Using Balancing Chemical Equations as a Key Starting Point to Create Green Chemistry Exercises Based on Inorganic Syntheses Examples, J. Chem. Educ. 2016, 93, 1330-1334.
J. Andraos*; A. Hent, “Simplified application of material efficiency green metrics to synthesis plans: pedagogical case studies selected from Organic Syntheses”, J. Chem. Educ. 2015, 92, 1820-1830.
J. Andraos*; A. Hent, “Useful material efficiency green metrics problem set exercises for
lecture and laboratory”, J. Chem. Educ. 2015, 92, 1831-1839.
J. Andraos, The Algebra of Organic Synthesis: Green Metrics, Design Strategy, Route Selection, and Optimization, CRC Press-Taylor & Francis: Boca Raton, 2012 (addresses many of the literature problems in green chemistry, balancing equations, importance of quantification)

The information on balancing chemical equations is added and three first references are cited. Unfortunately, our library does not have access to the fourth one. The following text is added:
The first and crucial step in application of any kind of metrics is balancing chemical equations. Material utilization efficiency is the simplest metric tool, so it should be taught before introduction of energy efficiency, environmental impact of hazards metrics. Application of synthesis tree diagram is an easy way to identify all substrates, intermediates and reaction steps in mass efficiency assessment. This visualization tool allows students to focus on more complex, multi-stage chemical reaction. There are many examples of the organic and inorganic reaction avialiable.

I would suggest that the authors re-organize the Conclusions section, perhaps by changing it to “Ongoing Challenges and Future Trends: areas for improvement in teaching and in research”.

The Title of this Section has been changed.

The areas of green chemistry education that need attention should be put in the first part of this section. The second part of this section should highlight the areas of green chemistry research that need addressing. This will improve 2 the structure of the paragraphs the authors have already written and give the reader a better understanding of the current status.In each part, the authors should make an effort to prioritize the issues if possible by separating each topic with bullet point notation.

The last section has been reorganized.

Below I suggest the following additional topics in no particular order:
Education
Balancing chemical equations especially in the study of organic chemistry courses (particularly reduction and oxidation reactions); and connect it with actual reaction mechanism, and not treat the exercise as a numbers game of balancing stoichiometric coefficients on the left and right hand sides. This will improve students’ understanding of why certain by-products occur in a given reaction – there is an underlying Chemical explanation for their creation.
Thank you very much for such important examples. These sentences have been incorporated into the text.

Incorporation of quantitative analysis of optimization in organic synthesis courses which are mainly taught from a qualitative perspective that emphasizes memorization of reactions and their names over other problem solving skills. This is directly related to the very poor mathematical skills of synthetic organic chemists who incorrectly believe that that skill is not needed in their work. Such people are guaranteed not to adopt green chemistry practices.

Thank you very much for such important examples. These sentences have been incorporated into the text.

The authors’ correctly point out that thermodynamics education for energy metrics is particularly pertinent but is likely to resonate in the green chemical engineering education, but less so in green chemistry education offered in Departments of Chemistry. Departments of Chemistry do not emphasize mathematical skill as part of the chemistry curriculum whereas Departments of Chemical Engineering do. Understandingthermodynamics requires considerable mathematical skill, which synthetic chemists are ill-equipped because of lack of training in their education.

Thank you very much for such important examples. These sentences have been incorporated into the text.

Instructors of undergraduates in traditional organic chemistry courses are weak in quantitative concepts – their only foray into mathematical concepts is via kinetic modelling which does not go beyond simple first-order and second-order behaviour.

Thank you very much for such important examples. These sentences have been incorporated into the text.

Connecting traditional experimental results and their write-up to metrics analysis as a mandatory requirement and distinguishing feature of green chemistry education. This link dramatically increases the student understanding of a given reaction, induces creativity in designing new experiments with new reactions to design optimized syntheses of their chosen target molecules, and increases student engagement overall. So far, there is no evidence in the JchemEd literature that this link has been made.

Thank you very much for such important examples. These sentences have been incorporated into the text.

Training students to identify “green-washing” in the chemistry literature which abuses the announcement of “green” improvements based on only one or two factors while ignoring everything else.
Thank you very much for such important examples. These sentences have been incorporated into the text.

There has to be better training for instructors before better training for students can take place – this point needs to emphasized by the authors.
Thank you very much for such important examples. These sentences have been incorporated into the text.

Research:
In addition to the specific points mentioned by the authors from reference 6 the following can be added.

The problem of using microwave irradiation as a panacea for “greening up” reactions without regard to an accompanying energy analysis.
This has been mentioned in the previous version of the manuscript and its still stated in this version.

Comparative analysis is the first and foremost concern of green chemistry practice for honest reporting. See below for a leading reference, particularly chapter 1: P. Tundo and J. Andraos (eds.), Green Syntheses Volume 1, CRC Press-Taylor & Francis: Boca Raton, 2014. (first attempt to introduce honest reporting of truly green procedures by comparative metrics analyses)
Thank you very much for such important examples. These sentences has been incooperate into the text. The reference has been cited.

There is a plethora of metrics in the literature often with different names for the same concept thus causing undue repetition and introducing artificial complexity when none is required. This re-branding problem makes researchers and educators sceptical of the field and ultimately impedes implementation of ideas. The following leading reference highlights this problem:
J. Andraos*, Useful Tools for the Next Quarter Century of Green Chemistry Practice –

A Dictionary of Terms and a Dataset of Parameters for High Value Industrial Commodity Chemicals, ACS Sust. Chem. Eng. 2018, 6, 3206-3214 (discusses ongoing problems of metrics literature; compiles a dictionary/glossary of 300 terms used in green chemistry education and research)
Thank you very much for such important examples. These sentences has been incooperate into the text. The reference has been cited.

Specific Comments:
Page 1, column 1, line 41
"This movement starts around almost three decades."
To
"This movement started almost three decades ago."
Corrected.

Page 1, column 2, line 3
"…and first time presented at United Nations"
To
"…and was presented for the first time at United Nations"
Corrected.

Page 2, column 1, line 45
"The students of this line had to complete…"
To
"The students of this line of study had to complete…"
Corrected.

Page 2, column 1, line 54
"Chemistry and technology of proecological…"
To "Chemistry and technology of pro-ecological…"
Corrected.

Page 2, column 2, lines 1-5
"New approach partially covers old program on protecting the environment but it puts the
stress on typical aspects of green chemistry in order to not cause environmental problems
instead of treat them."
To
"The new approach partially covers the old program on protecting the environment but it puts the stress on emphasizes typical aspects of green chemistry in order to not cause
environmental problems instead of treating them."
Corrected.

Page 2, column 2, line 42
"When green chemistry concept will be included in the study program…"
To
"When green chemistry concepts will be included in the study program…"
Corrected.

Page 3, column 1, lines 7-12
"The clutter of work is a presentation of a case study of green chemistry idea application
in study courses as well as the presentation of future trends in this field. The new way of
thinking about research and chemical education allows to arm students with the knowledge needed to effectively address the great challenges of the 21st century."
To
The clutter of work main thesis of this work is a presentation of a case study of the application of green chemistry ideas application in study courses as well as the presentation of future trends in this field. The new way of thinking about research and chemical education allows students to be armed with the knowledge needed to effectively address the great challenges of the 21st century."
Corrected.

Page 5, column 1, lines 17, 44-45
“Simple tools applicable to chemical reactions [34] are atom economy, mass intensity or stoichiometric factor allows obtaining the most basic information on reaction greenness.”
To
“Simple tools applicable to chemical reactions [34] are atom economy, process mass intensity, E-factor, stoichiometric factor allows obtaining the most basic information on reaction greenness.”
Corrected.

Page 9, column 1, line 37
Put reference number in square brackets rather than as a superscript.
Corrected.

Reviewer 2

1. Page 4, Educational materials for teaching
In this section, the authors point out only one reference, 12. Do the authors consider that this site depletes all other educational materials published? Are there any relevant articles about educational materials, for example, in Journal of Chemical Education or Chemistry Education Research and Practice, which are not in this site?
Figure 6 is a copy of the information presented on the first page of the website, reference 12; is it relevant to present the figure?

Thank you for this comment. This sub-section has been extended. Figure 6, has been deleted.

2. Page 4, Figure 7. Authors refer that figure presents information on published textbooks, lab manuals…Is it not explicit if there was a criterion to choose the documents; next a reference of a book, published in 2004: Green Organic Chemistry, Strategies, Tools and Laboratory experiments, Kenneth M. Doxsee and James E. Hutchison, Thomson, Brooks/Cole, ISBN: 0-534-38851-5. If the experiments are green, that is another aspect…

The published textbook presented in Figure 7 (now Figure 6) were selected by introduce of an appropriate keywords in Scopus, Clarivate Analytics and others. The recommended by you reference has been introduced.

3. Page 5, Green chemistry metrics education
In this section, the authors refer: Green chemistry is a very multi-aspect phenomenon and therefore it needs adequate tools to measure the degree of greenness of methods and procedures. Green chemistry metrics [33] is useful to see the differences between old-fashioned, conventional chemical processes and their green alternatives. Next they refer: Simple tools applicable to chemical reactions [34] are atom economy, mass intensity or stoichiometric factor allows obtaining the most basic information on reaction greenness.
However, reference 33 is, in fact, the article where D. J. Constable, A. D. Curzons and V.L. Cunningham presented the new metrics Reaction Mass Efficiency (RME) and Mass Intensity (MI) in 2002, mass metrics used since then in the evaluation of green chemistry processes, not forgetting E factor, presented by R. A. Sheldon in 1992. Reference 34 presents values of E-Factor in different chemical industries and refers MI, calling it also PMI (used by some authors instead of MI). The metric Atom Economy (AE), presented by B. M. Trost in 1991, indicates only the potentiality of the synthesis reaction to be more or less green in terms of the use of the mass of the stoichiometric reagents. The calculation is based in the molecular weights of the stoichiometric reagents and product, considering the stoichiometric coefficients, the formula is in reference 33. AE is a theoretical metric, based in the chemical equation of the synthesis reaction, the yield or the excess of stoichiometric reagents are not considered. The ideal value is 100% that happens when all the atoms of the stoichiometric reagents are incorporated into the product; in this case, byproducts are not formed. On the other hand, the value of RME is calculated simply by dividing the

mass of the product by the mass of the stoichiometric reagents. Solvents and other auxiliary reagents are not considered in RME (but are considered in the calculation of MI), and RME depends on the yield and on the excess of stoichiometric reagents, see reference 45 in your reference 34. Therefore, RME should be also considered in your list, because it deals with the mass greenness of the reaction chosen. Evaluation of mass greenness of a synthesis requires a battery of metrics.

Thank you for your comment. Yes, the greenness cannot be assessed with single metrics but multi-metric approach is required. RME is mentioned in our discussion.

4. For the GSK solvent guide referred in references 35 and 36, another reference (2016 Green Chem., 2016, 18, 3879, “Updating and further expanding GSK’s solvent sustainability guide”), not considered in references 35 and 36 should be added, as it is an important update.

The reference has been introduced.

5. Page 5, lines 21-24. The last paragraph of the section “Green chemistry metrics education” refers to “Teaching advances assessments for green chemistry” and to LCA assessments as “Different approaches to life-cycle assessments (LCA) are at the moment one of the most comprehensive and holistic ways of greenness assessment [41]. The teaching of LCA is beneficial…”. Only one reference of 2007, 41, is provided, but I could not access it. The authors do not give a summary of the main ideas of these approaches. There are some interesting articles from 2016 and 2017 in Journal of Chemical Education, Green Chemistry and Elsevier. A review “An overview of life cycle assessment (LCA) and research-based teaching in renewable and sustainable energy education” from 2017 (https://doi.org/10.1016/j.rser.2016.11.176) is interesting.

Following citations are added together with discussion:
The review on LCA in chemical education shows that such examples are rather scarce. However, the first experience from incorporation of LCA into chemical engineering programs improves critical thinking and problem solving students abilities. LCA improves the understanding of chemistry areas such as pharmacy, nanotechnology, flow chemistry and others.
K. Alanne, H. Makki, Ren. Sus. Energ. Rev. 2017, 69, 218-231.
D. Kralisch, D. Ott, D. Gericke, Green Chem., 2015, 17, 123-145.

Another holistic metric for assessment the greenness, “Green Star”, is referred in your reference 34 (reference 80), but not in your review; this metric has been updated see: J. Chem. Educ. 2013, 90, 432−439.

It is added to the discussion with proper reference: The semi-quantitative tools that are based directly on the 12 principles of green chemistry are green circle and green matrix.
M. Gabriela T. C. Ribeiro, A. A. S. C. Machado, 2013, J. Chem. Educ., 90, 432-439.

6. Page 6. In section Teaching Methods, lines 8-13, the authors refer “…the terminology of green chemistry would be standardized. For instance, the terms “E-factor”, “mass intensity”, “mass productivity” and “process mass intensity” all indicate metrics emphasizing the amount of material used in chemical processes [43]”. This is referred in page 70 of your reference 6, not in reference 43; Reference 43 refers important metrics such as Solvent Intensity, Water Intensity and Renewable Intensity, and also Mass Intensity (MI), Atom Economy (AE) and Reaction Mass Intensity (RME), and all of them mass metrics. All these metrics, permit to evaluate the mass greenness of syntheses, they all indicate metrics emphasizing the amount of material used in chemical processes, but they address different aspects that together give a more complete view of the mass greenness…

It has been corrected.

7. Page 6, line 25. The authors refer “However, adding a stand-alone course in an optional version to an already-crowded curriculum seems to be pointless [6]”, but reference 6 does not present that conclusion…

| | |
|---|---|
| | Thank you for your comment . This conclusion refers to the text on page 71 " A new course is time-consuming to prepare and may not find room within an already-crowded curriculum, especially if it is proposed as an elective(...) the "greening" of exisisting courses has the advantage of being less time-consuming in terms of implementation".<br><br>The sentence has been corrected : However, adding a stand-alone course in an optional version to an already-crowded curriculum seems to be much time-absorbing as for preparation and adaptation . |
| **Section/Category:** | |
| **Additional Information:** | |
| **Question** | **Response** |
| Submitted solely to this journal? | Yes |
| Has there been a previous version? | No |
| Do you or any of your co-authors have a conflict of interest to declare? | No. The authors declare no conflict of interest. |

# Green Chemistry in Higher Education: State of the art, challenges and future trends

Justyna Płotka-Wasylka*[a], Aleksandra Kurowska-Susdorf[b], Muhammad Sajid[c], Miguel de la Guardia[d], Jacek Namieśnik[a], Marek Tobiszewski[a]

**Abstract:** Nowadays, there is an increasing interest on world sustainability in our societies and, because of that, university students would like to know how human actions affect the health status of our planet. This is mainly due to their basic knowledge of such problems as global warming and greenhouse gases. Students would like to gain the knowledge how to safeguard the Earth for future generations. This must involve changes in education programs at interested institutions and universities. To ensure that the future chemist generation is equipped with the proper knowledge, significant efforts would be needed. Thus, this article aims to present the history of green chemistry and its milestones and also to give ideas how to teach this subject. Discussion on awareness in the field of green chemistry as well as on existing materials for teaching is presented. In addition, green chemistry metrics, which should be known and used by professors and students, are described. Teaching methods of green chemistry are also given, paying special attention to organic and analytical chemistry education.

## 1. Introduction

Green chemistry as well as chemical engineering focus on the design of products and processes that minimize the use and generation of hazardous substances and residues. This movement started almost three decades ago. However, it is necessary to note that many years before introducing the term "Green Chemistry", the context of increasing attention to problems of chemical pollution and resource depletion existed and was widely discussed. One of the big milestones of sustainable chemistry was introduction of The Ten Ecological Commandments for Earth Citizens (Figure 1) which were formulated by Peter Menke-Glückert at Organization for Economic Cooperation and Development (OECD) in Paris during 1966 to 1970, and was presented for the first time at United Nations Educational, Scientific and Cultural Organization (UNESCO) conference "Man and Biosphere" in Paris (1968)[1].


**Figure 1.**THE Ten Eco-Commandments For Earth Citizens presented by P. Menke-Glückert at UNESCO conference „Man and Biosphere" in Paris (1968)

Other milestones leading to the development of Principles of Green Chemistry, Green Chemical Technologies, Green Engineering and Green Analytical Chemistry are presented in Figure 2.

Without any doubt, Green Chemistry and Green sustainability has been a great social concern. People became more aware of the hazardous chemicals present in everyday products and manifest a demand for alternatives that are perceived to be safer. Such an approach brings a considerable pressure on manufacturers and also on the higher education system to take into account the consequences of hazardous chemicals and reduce their potential negative impact on humans health and the environment. Thus, many students today are profoundly interested in the sustainability of their world. In times of great industrial development and era characterized by growing public concern over global warming and greenhouse gases, students would like to understand how human activities impact on the health of our planet [2]. Considering students of chemistry, they have a special opportunity of starting at the ground floor of the exciting and expanding green chemistry field.

The idea of Green Chemistry has its roots in academic research and evolved becoming a mainstream practice supported by academia and by industry and government. To facilitate understanding this idea and to put it into practice, very specific principles of a chemical practice known as the Twelve Principles of Green Chemistry were introduced. The application of green chemistry and its practice has become of high importance and has extended internationally as an alternative to traditional industrial practice in developing countries. Without any doubt, this evolution, has been contributed by scientific units and appropriate awareness at various levels of education. In fact, education in green chemistry offers a solution to current

[a] Dr. Justyna Płotka-Wasylka*; Prof. Jacek Namieśnik; Dr. Marek Tobiszewski
Department of Analytical Chemistry
Gdańsk University of Technology, Faculty of Chemistry
11/12 G. Narutowicza Street, 80-233 Gdańsk, poland
E-mail: plotkajustyna@gmail.com
[b] Dr Aleksandra Kurowska-Susdorf
Faculty of Humanities and Social Sciences
The Naval Academy
69 Śmidowicza Street, 81-127 Gdynia, Poland
[c] Dr Muhammad Sajid
Center for Environment and Water
King Fahd University of Petroleum and Minerals,
Dhahran 31261, Saudi Arabia
[d] Prof. Muguel de la Guardia
Department of Analytical Chemistry
University of Valencia
50thDr. Moliner St., Burjassot, Valencia E-46100, Spain

common problems of environment since it ensures the opportunity of training future scientists, thus helping to move people toward a more sustainable society [3, 4].

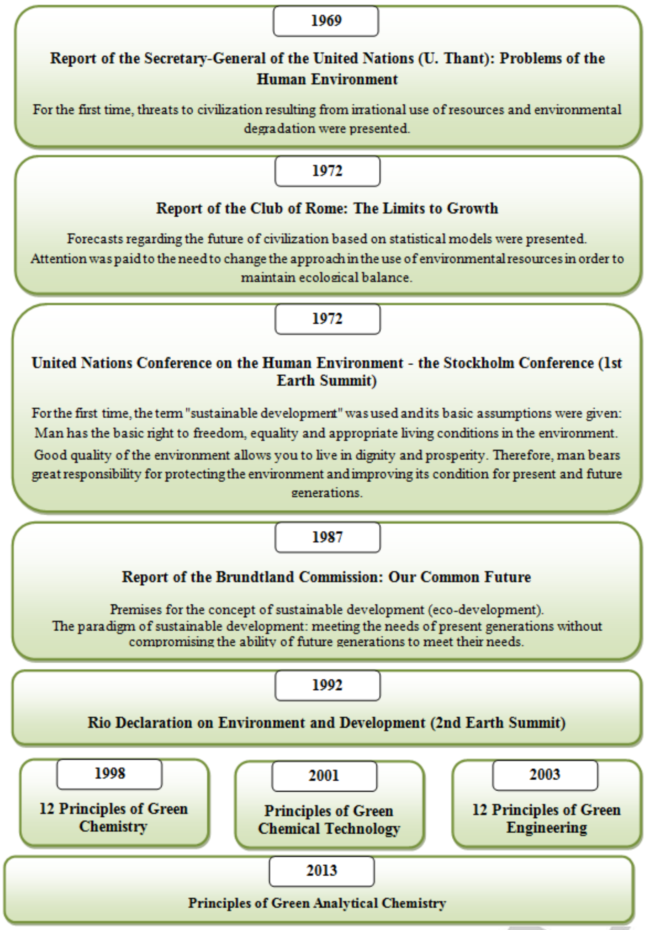



**Figure 2.** Milestones is development of Green Chemistry concept

An increasing number of institutions are now including concepts of green chemistry in their curriculum (Figure 3). One of the pioneers of this area was the Chemical Faculty of Gdańsk University of Technology, who understood that pro-ecological education is particularly important for the education of chemists and chemical engineers and thus introduced a program called Environmental Protection in 1992 which was run in English [5]. The students of this line of study had to complete the obligatory courses related to environment protection such as Air, Water, and Soil Protection; Elements of Environment Protection Science; Technology and Engineering of Environment Protection Systems; Pro-ecological Materials; Legal Regulations and Environment Protection; and Non-conventional Energy Sources. Moreover, elements of environmental knowledge were included in many other obligatory courses. During the sixth semester, the students select one of the three presently available graduation specializations: Chemistry and technology of pro-ecological materials, Monitoring and analysis of chemical pollutants of the environment, and Technologies of environment protection and waste utilization. To meet the expectations of the world needs, Chemical Faculty of Gdańsk University of Technology decided to introduce Green Technologies and Monitoring program (in English and in Polish) instead of Environmental Protection. This substitution was made to meet the trend in science and technology of introducing green chemistry concepts. The new approach partially covers the old program on protecting the environment but it puts the stress on emphasizes typical aspects of green chemistry in order to not cause environmental problems instead of treating them.

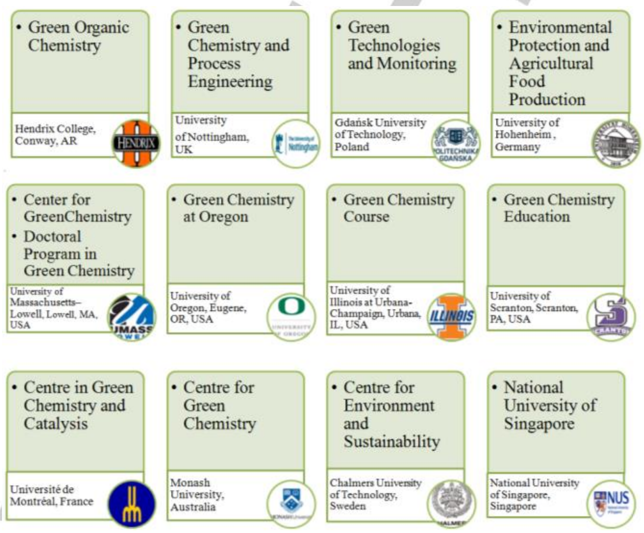



**Figure 3.** Selected institutions which include concepts of green chemistry in their curricula

In addition, some of the aforementioned institutions offer degrees in green chemistry. The ideas of programs conducting at these institutions should be viewed as inspiration and adopted by others. Such proceeding can help to overcome some of the persistent counter-arguments to green chemistry in the classroom [6, 7]. There is no doubt, that the incorporation of green chemistry concepts brings many benefits which are significant and applicable to all education levels [6, 7]. First of all, assumptions of green chemistry ensure the connection between the program of studies and the students' everyday environment, far beyond pollution, global warming, and ozone depletion. Here, several examples can be mentioned such as recycling feasibility and limitations, aspects of consumer product design sustainability, the efficiency of energy, and others. When green chemistry concepts will be included in the study program, not only students of the chemical sciences but those of all disciplines, will have the ability to relate chemical ideas to the "real world" and to their career path selection.

Due to the fact that chemistry-related courses are very rich and are based on a wide range of information related to various fields of science, it is hard to add additional contents as green chemistry teaching. In fact, many lecturers and scientists believe that green chemistry should not replace existing material, but existing classes should be taught in a new way, incorporating key concepts into the curriculum to make chemistry inherently green [4, 6, 7]. The result of these considerations is the creation of several concepts that should be applied to enhance the chemistry and chemical engineering curriculum (Figure 4).

Despite the fact that green chemistry exists for more than two decades, it is still a hot topic in research and education area. Thus, it is important to give comprehensive information about state of the art, challenges and future trends connected with this issue. Therefore, this article aims to present the history of green chemistry and its milestones together with information about how to teach this topic. Discussion on awareness in the field of green chemistry as well as on existing materials for teaching are presented. In addition, green chemistry metrics which should be known and used by interested people are described. Teaching methods of green chemistry are also given. Moreover, the way of teaching in specific fields such as organic chemistry and analytical chemistry is also discussed. The main thesis of this work is a presentation of a case study of the application of green chemistry ideas in study courses as well as the presentation of future trends in this field. The new way of thinking about research and chemical education allows students to be armed with the knowledge needed to effectively address the great challenges of the 21st century.

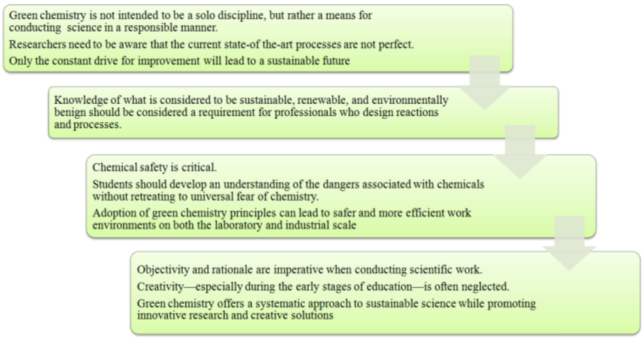



**Figure 4.** General concepts that should be applied to enhance the chemistry and chemical engineering curriculum

## 2. History of Green Chemistry

The major advancements regarding green and sustainable chemistry started a few decades ago after the sustainability movement. This also led to the establishment of guiding principles. From this perspective, the area of the green chemistry is still in its stage of infancy. However, the fact that greener chemical approaches were being practiced many decades before the recent developments should also be realized (see Figure 5). Several historical examples on the application of greener reaction solvents or elimination of toxic solvents can be found in the literature. Some of them have been presented in a recent review article [8].

After the industrial revolution, the role of chemical reactions and related products was significantly increased in different industrial applications. The excessive and indiscriminate use of toxic and health hazardous chemicals resulted in many problems for the human health and sustainable environment. Consequently, the concerns were raised. Rachel Carson's "Silent Spring (1962)" is the first publication which highlighted the impact of pesticides on the environment and raised public awareness regarding the use of such chemicals. Historically, this book is considered as the launch and basis of the modern environmental movement. After less than a decade of this publication, the Environmental Protection Agency (EPA) was established in 1970 in the USA.

| Green approach | Description | Reported date |
|---|---|---|
| Alternative solvents | Water as the solvent for urea synthesis from ammonium cyanate | 1828 |
| | Formation and use of ionic liquids | 1914, 1935 |
| Multi-component reactions | Preparation of dihydropyridines and dihydropyrimidones | 1882, 1893 |
| Solvent-free transformations | Disruption of silver chloride by mechanical force (mechanochemistry) | 1892 |
| | Dry reaction between $HgCl_2$ and KI upon grinding | 1914 |
| | Synthesis of 2,4-dichlorophenoxyacetic acid (component of Agent Orange) | 1949 |
| Catalysis | Organocatalysis of condensation reactions by amines | 1899, 1990, 1937 |
| | Enzyme-catalyzed organic reactivity | 1906, 1908 |
| | Vitamin B1 (thiamine) biocatalysis of condensation reactions | 1958 |
| Biofeedstocks | Synthesis of furfural and levulinic acid (used to make 2-methyltetrahydrofuran, a greener solvent) from corn cobs and cane sugar, respectively | 1921, 1929 |
| Sonochemistry | Reaction rate enhancements by high frequency sound waves | 1927 |
| Greener reagents | Pyridinium tribromide as an alternative brominating agent to molecular Br2 | 1948 |
| | Deep eutectic solvents as an alternative to popular solvents | 2001 |
| | Natural deep eutectic solvents introduced | 2003 |
| Extraction with Greener solvents | Coacervate-based extraction | 1970's |
| | Supercritical fluid extraction | 1992 |
| | Superheated water extraction | 1994 |
| Ionic liquids and extraction | The first report on utilization of ILs coupled to single drop microextraction | 2003 |
| | ILs used in solid phase microextraction | 2005 |
| | ILs used in dispersive liquid-liquid microextraction | 2008 |
| | Vortex-assisted IL microextraction was reported | 2013 |

**Figure 5.** Selected historical examples of green chemical approaches in organic chemistry, industry and analytical chemistry

The Stockholm Conference on the Human Environment (1972) and the World Conservation Strategy of the International Union for the Conservation of Nature (1980), helped the world leaders to understand and realize the importance and need for the sustainable development [3]. In the 1980s, this movement emphasized on the prevention of pollution at first place instead of developing strategies for the control of pollution. Hence, in 1988, the Office of the Pollution Prevention and Toxics was established within EPA which launched a research program called "Alternative Synthetic Pathways for Pollution Prevention". This program provided extraordinary grants for research projects that focus on pollution prevention in the design and synthesis of chemicals. Following that, in 1990, a pollution prevention bill was passed which landmarked a major policy shift from pollution control to pollution prevention. Later, in the early 1990s, the term of "Green Chemistry" was introduced [3].

Despite all the historical background regarding the need for sustainable practices in chemistry, the major literature describing the guiding principles, curriculum development, and different aspects of green approaches emerged within last three decades. To promote and develop the concept of Green Chemistry in teaching and research effectively, it was necessary to integrate it into the coursework of undergraduates and graduates. Moreover, there was a special need to establish institutes and departments within the academia to launch the courses, research, and degree programs in the area of green chemistry. In this regard, the first-course "Introduction to Green Chemistry" was offered at Carnegie Mellon University and described in the Journal of Chemical Education (JCE) [8]. In 1997, Green Chemistry Ph.D. program was launched by the University of Massachusetts at Boston. In the same year, Green Chemistry Institute (GCI) was established to advance the green chemistry through research, education, conferences/deliberative symposia/meetings, and information dissemination including public awareness.

In 1998, Anastas and Warner published their famous book “Green Chemistry: Theory and Practice” where they described Twelve Principles of Green Chemistry. These principles provided clear guidelines to practice and implement green chemistry in routine chemical processes and reactions [9]. Realizing the importance of the green chemistry in teaching and research, Royal Society of Chemistry launched its journal “Green Chemistry” in 1999 to provide a platform to the researchers for publishing the progress in the area. In August 2000, an alliance was made between ACS and GCI to further the area. Later, many new journals, conferences, research awards, and centers were launched throughout the globe.

## 3. Teaching green chemistry: challenges

### 3.1. Awareness in the field of green chemistry

Since the entry of society into the new century, in the face of the worsening condition of the environment, people have become more and more conscious of environmental protection. Thus, the concept of "green chemistry" has gradually begun to be widely applied in various social life fields [10]. Although the idea of green chemistry exists for more than two decades, there is still growing awareness all over the world, particularly in academia, industry, and the general public, of the need for sustainable environment and development [11]. This is due to increasing pressure at the international chemistry community to change current working practices as well as to find greener alternatives to the traditional processes and methods. In addition, several issues should be changed in educational programs. Moreover, engineers and scientists from the academic world as well as from the chemical industry are making efforts to avoid and reduce pollution problems by the extensive application of principles of green chemistry. In fact, the development and introduction of modern methodologies and products that are eco-friendly is the order of the day in any industrialized nation in the world. However, such initiatives are far to gain ground in the developing nations, particularly in nations where environmental consciousness, as well as accounting, meant little or nothing to the citizenry [12].

Generally, in the industrial field, people's environmental protection awareness is increasing. Therefore, the design of chemical products has evolved from the traditional and popular trend of “only the economic interests maximization” to “making environmental goals a standard and weighing not only the economic factors but also social development, ecological environment and other aspects of the content to carry out design work” [10]. It is important to take full account of the development and research, production, waste recycling, and other chemical product aspects in the phase of design rather than thinking about the methods to deal with the final waste when processing the products, or even after the products have been produced and the application has been scrapped [10]. Such proceeding is important due to the fact that the overall framework of chemical product design will directly determine the extent of the impact on the ecological environment. However, in order to learn the way of doing such a thing, proper education becomes important.

### 3.2. Educational materials for teaching

To speed the incorporation of pollution prevention into everyday life as well as into industrial manufacturing processes, it is important to develop the green chemistry curriculum materials. To facilitate the introduction of green chemistry into the classroom, many of the organizations, for example, the Analytical Chemistry Society (ACS) Division of Education and International Activities and EPA-OPPT designed materials to provide succeeding chemists generations with the knowledge to practice green chemistry. On the website of ACS [13], tools which can help in the lab, curriculum ideas for teachers, local government resources are shortly discussed. References to this information are given too. This internet-based database holds a searchable collection of articles, green chemistry books, courses, demonstrations, laboratory exercises, and other databases. In addition, it needs to be stated that this database serves the function of increasing access to information as well as resources connected to green chemistry, what impacts on extending capabilities by supplying quality materials, and reducing the potential barriers to communication.

In addition to teaching tools mainly available online, textbooks, reference materials, and lab manuals have been published in this area. Several examples of such materials are presented in Figure 6. They were selected by introduce of an appropriate keywords in Scopus, Clarivate Analytics and others..

| Branch of science | Title | Education level | Ref. |
|---|---|---|---|
| Organic Chemistry | „Green Techniques for Organic Synthesis and Medicinal Chemistry” | Undergrad chemistry majors through professional | 14 |
| | „Green Organic Chemistry, Strategies, Tools and Laboratory experiments” | | 15 |
| | „ Organic Chemistry and Its Interdisciplinary Applications ” | | 16 |
| Engineering Chemistry | „Innovations in Green Chemistry and Green Engineering: Selected Entries from the Encyclopedia of Sustainability Science and Technology” | Undergrad chemistry majors through professional | 17 |
| | „Green Chemistry & Engineering: A Practical Design Approach” | | 18 |
| | „Green Chemistry and Engineering: A Pathway to Sustainability” | Undergrad chemistry and engineering | 19 |
| General Chemistry | „Introduction to Green Chemistry, 2nd Edition” | Undergrad chemistry majors through professional | 20 |
| | „Green Chemistry Fundamentals and Applications” | | 21 |
| | „Green Chemistry Laboratory Manual for General Chemistry Csm Lab Edition” | Undergrad | 22 |
| | „Chemistry in Context, 8th Edition” | Undergrad, non-chemistry majors; Intro to chemistry | 23 |
| | „Chemistry for Changing Times, 13th Edition” | | 24 |
| Analytical Chemistry | „Handbook of Green Analytical Chemistry” | Undergrad chemistry majors through professional | 25 |
| | „Challenges in Green Analytical Chemistry” | | 26 |
| | „Green Chromatographic Techniques: Separation and Purification of Organic and Inorganic Analytes” | | 27 |
| | „Green Analytical Chemistry” | | 28 |
| | „Green Extraction Techniques: Principles, Advances and Applications” | | 29 |
| Renewable Resource and Sustainable Science | „Fundamentals of Environmental and Toxicological Chemistry: Sustainable Science” | Undergrad chemistry majors through professional | 30 |
| | „Efficiency and Sustainability in the Energy and Chemical Industries, 2nd Edition” | | 31 |
| | „Introduction to Chemicals from Biomass” | | 32 |
| | „Experiments in Green and Sustainable Chemistry” | | 33 |

**Figure 6.** Information on published textbooks, reference materials and lab manuals after 2005 year in the area of green chemistry and related field [14-33]

Moreover, dry computer-aided assessment as well as improvement tools that can be applied in green engineering exist. These tools can be helpful during performing of each of stage of engineering process such as [34] :

i) inform process or product design early on through rating of chemical process as well as environmental properties,
ii) through process simulation and environmental fate modeling,
iii) ultimately by using process integration and multi-objective optimization."

The tools can be applied for a range of scales, including molecular, process, national, or even global. These tools are incorporate in green engineering in a hierarchical design sequence.

These computer-aided tools can be applied for specific purposes such as:

i) early design evaluation to forecast environmental properties, select of the green chemistry options, and design molecules with lower environmental impacts; here, such tools as the Program for Assisting the Replacement of Industrial Solvents (PARIS II) [35],
ii) environmental impact assessment of process designs; here, such tools can be used: Waste Reduction Algorithm [36]; tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) [37];
iii) the estimation of pollutant release from processes to the air; here, such tools can be used [38]: Air CHIEF CD, TANKS 4.0, CHEMDAT8.

### 3.3. Green chemistry metrics education

One of the crucial aspects in green chemistry education concerns green chemistry metrics. Green chemistry is a very multi-aspect phenomenon and therefore it needs adequate tools to measure the degree of greenness of methods and procedures. Green chemistry metrics [39] is useful to see the differences between old-fashioned, conventional chemical processes and their green alternatives. If students know these differences, they could be truly convinced that green chemistry brings advantages. Simple tools applicable to chemical reactions [40] are atom economy, reaction mass efficiency, process mass intensity, E-factor, stoichiometric factor allows obtaining the most basic information on reaction greenness. The semi-quantitative tools thatare based directly on the 12 principles of green chemistry are green circle and green matrix [41]

The first and crucial step in application of any kind of metrics is balancing chemical equations. Material utilization efficiency is the simplest metric tool, so it should be taught before introduction of energy efficiency, environmental impact of hazards metrics [42]. Application of synthesis tree diagram is an easy way to identify all substrates, intermediates and reaction steps in mass efficiency assessment [43]. This visualization tool allows students to focus on more complex, multi-stage chemical reaction. There are many examples of the organic and inorganic reaction available [44].

As green chemistry is not only concerned about reaction efficiency, it is beneficial to incorporate other assessment aspects in teaching as energy utilization, toxicity of reagents, solvents, and auxiliaries. For proper energy consumption assessment, it is obligatory to incorporate in curricula thermodynamics. In order to select more benign reagents [45], solvents [46, 47] and auxiliary substances [48], selection systems should be discussed. They are basic tools in searching for greener alternatives, they contain a great overview of alternatives and, what is the most important, they are a good starting point for the discussions on criteria that reflect the greenness of chemicals.

Another important aspect that should be taught is the responsibility for generated waste in form of good waste management practices [49]. First of all quantitative aspect of generated waste should be introduced. Students should be able to identify what materials are qualified as waste. Next point is introducing the methods to quantify waste. This is not always easy, as wastes are generated not only in form of easily quantifiable solid waste but also as liquids and vapors in form of highly dispersed pollution. This leads to the introduction of the advanced topic of qualification of wastes from benign that can be emitted to the environment, such as water, to proper waste managerial practices. Students ability to quantify and qualify wastes is a natural way to be able to shift chemical processes waste management from storage, dispersion and "end of pipe" approaches to waste recycling, industrial synergies and zero-waste technologies [50].

Apart from metrics for green chemistry students should be able to perform simple economic assessments of chemical processes, substrates, products, intermediates, and auxiliaries. Calculations of costs are important as many of greener alternatives are also economically favorable in comparison to traditional solutions, thus offering an additional interest [51]. Students as future chemists or chemical engineers must be able to support green choices with economic arguments.

Teaching advances assessments for green chemistry is also of great importance. Different approaches to life-cycle assessments (LCA) are at the moment one of the most comprehensive and holistic ways of greenness assessment [52]. The teaching of LCA is beneficial as making of inventories of mass and energy flows to give information on the greenness and deep understanding of chemical process in other aspects like engineering way. The review on LCA in chemical education shows that such examples are rather scarce [53]. However, the first experience from incorporation of LCA into chemical engineering programs improves critical thinking and students abilities to solve problems. LCA improves the understanding of chemistry areas such as pharmacy, nanotechnology, flow chemistry and others [54].

## 4. Teaching methods

The main purpose of education is to shape responsible citizens and stewards of the earth [55]. The main logic of interest in green chemistry education faces the challenge of solving the side problems caused by chemistry to the environment and human beings, also evidencing that the chemistry knowledge could be a part of problems solution and not only a reason for those environmental troubles. Regardless of pedagogical traditions, education about green chemistry is significant for a sustainable future and should be infused across the curriculum. It is an educational imperative to teach the significance of green chemistry to future chemists and also future health professionals, educators, politicians and economists [3].

The objectives of green chemistry education, shared in the American and Chinese curricula are common and revolve mostly around; improving people's knowledge about chemistry, use of renewable resources, avoid unfavorable effects of chemistry on the environment and human health. Whereas China represents a strong context-oriented approach to green chemistry education, American educators prefer laboratory-oriented content (inquiry-based learning). Teaching Green chemistry in both cases is process oriented, either on laboratory activities or project works including problem-solving strategy which serves meaningful learning [3].

Educators are facing challenges of concept and green principles to teach and to which literature direct their students to. During the third annual American Chemistry Society Green Chemistry Summer School (GCSS) in Canada, the need for relevant and updated resources was reported. Additionally, it was noted that education as a whole would benefit significantly when green chemistry was incorporated in every level of education, from elementary to graduate course [7]. The sustainability movement in Higher Education has gained attention facing ongoing challenges. To enable direct and effective application of the Twelve Principles there is a growing need of expanding pedagogical materials from various chemical subdisciplines such as analytical, environmental and physical chemistry where the terminology of green chemistry would be standardized. For instance, the terms "E-factor", "mass intensity", "mass productivity" and "process mass intensity" all indicate metrics emphasizing the amount of material used in chemical processes [7]. Furthermore, another challenge in teaching green chemistry is that its content is usually presented as optional, outside the core material. The quantitative analysis of syntheses is rarely an integral part of the chemical education and thus green chemistry is often seen as a descriptive subject with only numerous analysis required. Such "soft" skills expected in quantitative approach are considered in academia as unnecessary in synthetic organic chemistry courses [3,7].

Instructors searching for most effective teaching methods may face the dilemma how to organize green chemistry education. The pedagogical findings show that both, separate course on green chemistry as well as the integration of content with an already existing program, are acceptable. However, adding a stand-alone course in an optional version to an already-crowded curriculum seems to be much time-absorbing as for preparation and adaptation [7].

The shift in learning paradigm towards problem-based learning (PBL) approach has also a significant impact on chemistry studying strategies. Problems posed in the field of green chemistry, as well as in any educational fields, need multiple solutions where negotiations, case studies, and multivariate answers are possible and expected. Students need a shift in thinking about chemistry as a field with one correct "green" answer but rather accept the comparative strategies and decision-making approach.

Effective teaching methods and resources with regard to the chemistry as an experimental science, governed by optimization, prioritization of variables compromise the following aspects [3,7]:

i) use of innovative, up-to-the-minute case studies in practical components of courses;
ii) choose current green literature suitable for students at different levels;
iii) online, up-dated repositories of successful teaching modules, conferences and real-world organic teaching and industrial chemistry examples;
iv) use of laboratory setting, application of quantitative comparison between the reaction and critically evaluate transformation from a green perspective;
v) apply green chemistry principles (the Twelve Principles) in a comparative exercise;
vi) give students responsibility to plan and incorporate a number of sustainable strategies and make a decision;
vii) tell students the background story behind the discovery to help them memorize and illustrate the reaction, understand circumstances, mechanics, and motivation of the real research in an industrial setting (an example of three industrial syntheses of beta-carotene);
viii) pay more attention to quantification of energy consumption and costs for chemical reactions
ensure that students learn to adopt balances modus operandi when assessing "greenness".

## 5. Education in specific fields

Environmentally friendly chemical techniques are gaining importance in academic as well as in industrial research laboratories. Application of Green Chemistry has been slowly introduced in teaching laboratories due to the lack of published materials on this subject. However, recent developments in many fields of chemistry such as organic chemistry and analytical chemistry provide opportunities to initiate this material in teaching laboratories. In fact, not only science but also humanities are trying to introduce the idea of Green Chemistry in the educational program what is of high importance.

### 5.1. Organic chemistry

In the last two decades, one of the most dramatic changes that have taken place in the laboratory of organic chemistry has been the growth and development of the microscale movement. While the scale of processes and syntheses has been downscaled did not signify a pedagogical change on the part of organic teachers, there is no doubt that the revolution of microscale did affect the organic students learning experiences. Surely, it was required to learn how to work carefully in case of performing experiments on a small scale [56]. As an outcome, the technical skills and manual dexterity of students have been improved. In addition, the microscale revolution has exposed students to a greater variety of experiments [56]. Why? Mainly due to the fact that chemicals that are dangerous, expensive, or difficult to handle on the macroscale are often not doubtful on the microscale. As a result, students performing experiments on microscale level are much more likely to be exposed to reactions such as phase-transfer catalysis, alkylation, hydrogenation or Wittig [57-59]. It needs to be mentioned that unlike common educational reforms are temporary or affect only selected groups, the approach of microscale has both, spread and persistent.

In the late seventies, it was argued against the use of cookbook organic laboratories which were blindly followed by students without thinking about what they are doing [56,60]. Notwithstanding, ten years later, it was indicated that concerns about cookbooking as well as questions about how to best engage students of organic laboratory persist. In fact, the education community of organic chemistry has been very far from silent about the issue of cookbooking, and the response has been diverse and prolific. This resulted in the introduction by organic chemistry educators of three principle approaches which should encourage students to be more focused and thoughtful in the laboratory. These approaches can be broadly divided into three categories: discovery, inquiry, and project-based (Figure 7). Typical discovery experiments are based on the synthetic puzzles in which students need to discover the starting material and/or product identity or to deduce the regioselectivity or stereoselectivity of a reaction [56]. These unknowns can be obtained by application of spectroscopy methods such as infrared and nuclear magnetic resonance.

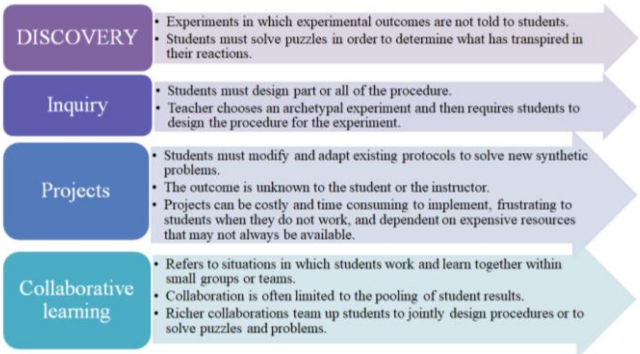



**Figure 7.** Information on teaching methods applied in organic laboratories

Less popular discovery-based experiments try to encourage students to discover the basic principles that underlie on purification techniques [61,62]. Due to the fact that discovery-based experiments and puzzles oblige students to focus and think about their experimental results, they discourage cookbooking.

In another potential solution to the problem of students robotically following recipes is an inquiry approach, in which the teacher or instructor chooses an archetypal experiment and next, requires students to design the procedure for the experiment [56]. Despite the fact that these approaches are not uncommon in the general chemistry laboratory [63,64], they have rarely been applied in the organic laboratory [65,66]. This can be due to the fact that organic protocols are more complex and that their design requires much more student knowledge and experience.

The last method applied to combat cookbooking is the project-based approach. This approach is much more prevalent than the inquiry method, however, it is less popular than discovery approach. Here, students need to work on multiweek research-like projects and must modify and adapt existing protocols to solve new synthetic problems [56]. The project can be open-ended what means that students are free to conduct any synthetic experiment that interests them or can be more narrow in scope. In the last type of projects, the instructor is the person who chooses the research question. This question may include synthetic route, target molecule, or functional group transformation. Both of these types of project require students to perform a primitive form of research in which they must conduct reactions that have never been tried before [56]. Due to the fact that project-based approaches more or less oblige students to think about the procedure as well as outcome, projects followers argue convincingly that projects successfully eliminate cookbooking.

In addition, these three approaches have also ushered in another pedagogical advance, namely collaborative learning. The ideology of this mode is based on the creation of such working conditions in which students can learn and work together within small teams or groups [67]. To facilitate and enable independent thinking, many instructors have turned to collaborative learning as a means of assisting students in negotiating. It needs to be pointed out, that most of the collaborative laboratories are project-based approaches that group students into synthetic groups that are responsible for everything from literature searching, to conducting reactions, to analyze experimental results [56].

### 5.2. Green analytical chemistry

To teach Green Analytical Chemistry, it is necessary to distinguish between contents and attitudes or models. Authors are absolutely convinced that the university cannot be just a professional formation centre and thus, contents about chemical knowledge must be incorporated in the general frame of problem-solving models, based on the deep and serious evaluation of data and particular situations. So, green analytical chemistry will be considered from the environmental and safety risks of chemicals handling and aspects regarding miniaturization, automation, and, particularly, evaluation of toxicity and characteristics of reagents and solvents commonly employed in the laboratory which could be related with method development and application.

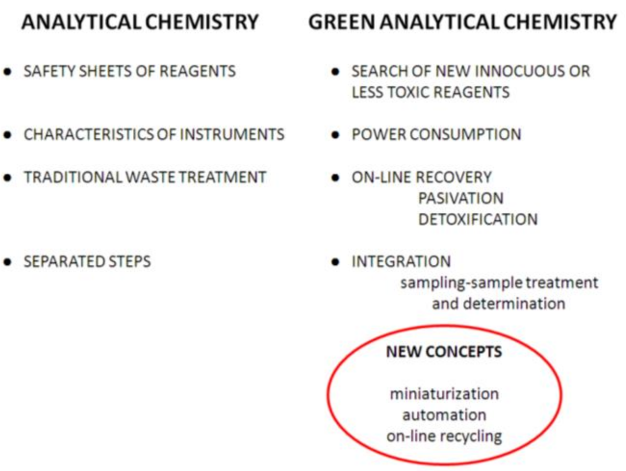



**Figure 8.** Schematic representation of the main concepts for teaching Green Analytical Chemistry

Education in green analytical chemistry would balance ethical and chemical aspects. An education on the social responsibility of analytical chemists [25] involves trueness of data through the deep evaluation of sample representativeness, method accuracy and selectivity and also a consideration of the risks for operators and side effects on the environment of analytical steps. The idea is to convince our students on the fact that chemistry is not only a risk for the planet, offering serious opportunities for health care and environmental problems remediation, and our obligation is to be able to transmit it.

The main concepts for teaching green analytical chemistry are summarized in Figure 8. They are strongly related to the consideration of analytes at the molecular level, thus paying attention to their evolution and toxic effects. Because of that, integration, together with sustainability, are the main concerns of green methods to move from safety sheets and characteristics of instruments to make decisions that could delete, or at least reduce, the deleterious effects of energy and reagents consume [25,26,49].

A particular aspect of green analytical chemistry is the need to incorporate the tools to move from traditional analysis to green one in the laboratory practices. It will reinforce the concepts concerning the evaluation of method greenness together with miniaturization and automation efforts, the consideration of possibilities to reduce energy and labor consumes and a general discussion of environmental risks and opportunities offered by the consideration of wastes as a responsibility of method developers and users.

Quantification of reagent and solvent amounts employed to do the analytical measurements together with their associated risks is in the base of method selection. Other aspects concern energy consumption and waste quantification and their associated risks. The main objective of the aforementioned aspects being to take opportunities in order to save consumes and look for the added value of operations like the on-line recovery of solvents and reagents. One of the most attractive aspects of green analytical chemistry is the possibility to reduce, simultaneously, the costs of analytical operations together with their associated environmental side effects. However, in this virtuous equation, the analytical features must be preserved to maintain the accuracy, sensitivity, selectivity, and precision at the required levels to solve the problems [25,26].

It can be noticed that on scaling down the amount of samples, standards and reagents use, it is possible to improve method sustainability, but it is also true that additional efforts must be done to protect sample and data representativeness in spite of the fact that method application involved a reduce amount of sample mass.

On the other side, automation always involves an enhancement of method greenness due to the reduction of operator risks and the possibilities for reagents and waste economy. This last point is based on the fact that reagents, non-mixed with other ones or with samples, can be stored and reused in another working session.

Concerning the on-line treatment of wastes, it provides a way to reduce risks of toxics accumulation in the laboratories and permits, from the education point of view, to create a social conscience of the students, minimize costs for the institution and incorporate experiments in this sense. So, it could be extremely beneficial for the students formation to incorporate at the end of the measurement steps aspects regarding thermal-, oxidation-, photo-assisted degradation, and biodegradation. These procedures can be incorporated into the methods additionally than the on-line distillation of solvent for their recovery. Particularly important in this aspect are the strategies for the reduction of the amount of water solution wastes containing traces of toxic non-degradable mineral elements. It could be done through precipitation and passivation of toxic ionic species obtained from method application, thus reducing costs and risks of waste transport and treatment [25,26,49]. It will put the stress on the benefits of degradation and passivation chemical reactions, at the molecular level, to move from wastes to clean wastes .

In short, it is important to complete the theoretical explanations with laboratory experiments and also with the example of professors in order that students could develop good laboratory habits to protect their health and the environment.

### 5.3. Humanities

Not only those involved in scientific fields but also professionals from humanities need to be aware of the possible unintentional consequences of harmful chemicals that may influence children and adults in low-income social groups. In recent years, non-government organizations have also brought into light the need to produce goods that advance justice, increase ecological resilience, and are safe for all human beings through their lifecycle. They deal with green living resources; green cleaning, greening healthcare, cleaner cosmetics, protecting pets [68] or focus mainly on greening food industry while building nutrition awareness [69-72]. Integration of a green chemistry course with non-science related modules in areas of law, ethics or business or the “greening” of existing courses appears to be more efficient in respect of implementation [69-72]. The emphasis on green chemistry in education on every level may play an essential role in moving society towards a positive, sustainable direction [73]. All people, regardless of age, profession and economic status have the same right to live, learn and work in the healthy environment. However, caring for social justice requires proper knowledge and effective educational methods.

## 6. Ongoing Challenges and Future Trends: areas for improvement in teaching and in research

As everyone knows, chemistry dramatically influences everything from the individual life to society as a whole. In the sustainable development context, learning is equivalent to troubleshooting of how to sustainably shape the future in specific action fields, including chemistry and its green aspects and chemistry education. Without a doubt, chemistry curricula as well as chemistry teacher education should more accurately reflect not only the education and sustainable development significance but rather should promote and support the human identity development which is undoubly correlated with the environment. Thus, the goal of chemical educators should be to allow students to actively learn how to shape society in a positive, sustainable fashion [4]. This is the first step of green chemistry education and need the special attention. The second important issue is to incooperate of green principles into educational practice because such proceeding may bring many advantages afforded to undergraduates. Examples of important skills typically acquired from green chemistry practice are outlined below (Figure 9).

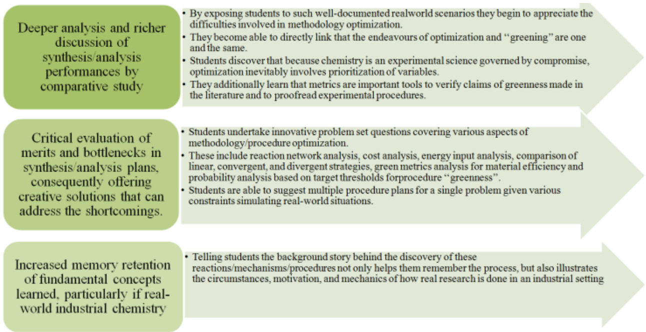



**Figure 9.** Benefits coming from inclusion of green principles into educational practice

Unfortunately, there are many gaps and areas for improvement in teaching and research.

First of all, the teaching style itself such as the presentation how to understood the laws of chemistry, reaction recording style, etc. should be changed. The following points are examples of another areas that need to be impoved:

i) Balancing chemical equations especially in the study of organic chemistry courses (particularly reduction and oxidation reactions); and connect it with actual reaction mechanism, and not treat the exercise as a numbers game of balancing stoichiometric coefficients on the left and right hand sides. This will improve students' understanding of why certain by-products occur in a given reaction – there is an underlying chemical explanation for their creation;

ii) Incorporation of quantitative analysis of optimization in organic synthesis courses which are mainly taught from a qualitative perspective that emphasizes memorization of reactions and their names over other problem solving skills. This is directly related to the very poor mathematical skills of synthetic organic chemists who incorrectly believe that that skill is not needed in their work. Such people are guaranteed not to adopt green chemistry practices;

iii) Application of examples from process chemistry from the pharmaceutical industry has been the standard approach to bridge the gap but there are other resources from other sectors from the chemical industry that can be used;

iv) The authors' correctly point out that thermodynamics education for energy metrics is particularly pertinent but is likely to resonate in the green chemical engineering education, but less so in green chemistry education offered in Departments of Chemistry. Departments of Chemistry do not emphasize mathematical skill as part of the chemistry curriculum whereas Departments of Chemical Engineering do. Understanding thermodynamics requires considerable mathematical skill, which synthetic chemists are ill-equipped because of lack of training in their education.

v) Instructors of undergraduates in traditional organic chemistry courses are weak in quantitative concepts – their only foray into mathematical concepts is via kinetic modelling which does not go beyond simple first-order and second-order behavior.

vi) Connecting traditional experimental results and their write-up to metrics analysis as a mandatory requirement and distinguishing feature of green chemistry education. This link dramatically increases the student understanding of a given reaction, induces creativity in designing new experiments with new reactions to design optimized syntheses of their chosen target molecules, and increases student engagement overall.

vii) Training students to identify "green-washing" in the chemistry literature which abuses the announcement of "green" improvements based on only one or two factors while ignoring everything else.

All of these issues give an important conclusion: there has to be better training for instructors before better training for students can take place.

Besides gaps in education and teaching, some also exist in literature and research area. The simplest example is that several false "greenness'' claims exist in the chemical literature. Many researchers state that a given procedure is green based only on one of the Twelve Principles of Green Chemistry. Such proceeding depicts a very narrow point of view rather than a multidimensional global approach which considers all reagents, material and energy consumption, as well as the environmental impact of any waste and by-products manufactured. A good example of such proceeding is the declaration about a procedure/reaction that is "solvent-free or solventless". Other examples in the research area are as follows:

i) The frequency of revealing the performance of reaction in patents is much lower than in journal publications, which impacts on the metrics assessment of good industrial examples adopted from the patent literature to depicture ideas of green chemistry. The plans and reactions assessment should include ionic liquid solvents synthesis and also specialized catalysts and ligands, as these are customarily omitted from the evaluation of the main green parameter evaluation of synthesis.

ii) The evaluation of energy consumption is often not disclosed as part of the standard protocol in experimental procedures reporting. In particular, such proceeding becomes problematic for proper evaluation of microwave-based chemical transformations against common, conventional heating methods since these are often cited as greener than traditional procedures, with little convincing hard evidence [6]. Generally, in publications only some fragmented combination of few parameters including reaction time, power consumption in watts, or temperature of reaction are given, while the intrinsic efficiency of the microwave apparatus applied is not taken into account, what affects the difficulties in determination of the actual energy consumption.

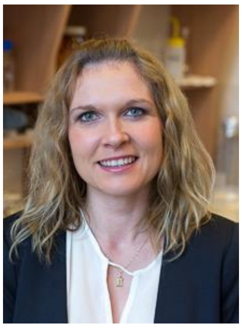
iii) Comparative analysis is the first and foremost concern of green chemistry practice for honest reporting [74] .

In addition to mentioned above problems, certain gaps become apparent in the educational literature. One important example is connected with catalytic reactivity which has been heavily exploited in student laboratories, but only a few examples are provided in the literature to inform on recycling and reuse of catalysts [75].

Widespread success in these and associated fields may lead to a re-writing undergraduate textbooks as a paradigm shift evolves [7]. Finally, as mentioned, energy consumption quantification, as well as costs for appropriate methodology, has received little attention from both, research and teaching perspectives.

In addition, there is a plethora of metrics in the literature often with different names for the same concept thus causing undue repetition and introducing artificial complexity when none is required. This re-branding problem makes researchers and educators sceptical of the field and ultimately impedes implementation of ideas [76].

Taking into account the analytical chemistry field, recent trends in extraction techniques have largely focused on finding solutions that minimize the use of solvents, what impact on downscaling of the whole procedure. In addition, novel solvents are applied for extraction. All of this affects the emergence of new extraction techniques which need to be known for students. Thus, new textbooks, as well as scholarly materials, will be published in next years.



*Justyna Płotka-Wasylka graduated from the Gdańsk University of Technology (GUT) with a Ph.D. in Chemical Science in 2014, after which she started work at the GUT (Department of Analytical Chemistry). Her research interests include the green analytical chemistry, elaboration of new analytical procedures for bioactive compounds determination in food and alcoholic beverage samples, the application of microextraction techniques in sample preparation process, the application of spectroscopic techniques to metals determination in food and alcoholic beverage samples, the application of gas chromatography-mass spectrometry to bioactive compounds determination in food and alcoholic beverage samples. She is the author of 30 scientific papers from JCR list of total impact factor equal to 181; number of citations (excluding self citations): 289, h-index: 7 (according to Web of Science, 12.02.2018).*

*Aleksandra Kurowska-Susdorf (born 1983) Ph.D, adjunct at the Institute of Educational Studies at the Faculty of Humanities and Social Sciences of the Naval Academy in Gdynia. Her scientific interests include thanatopedagogy and death studies. She also works on global education, environmental education as well as education for sustainable development among children and future teachers.*

*Muhammad Sajid received his Ph.D. degree in Chemistry from King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia in 2016. He is working as Research Scientist (III) at Center for Environment and Water, Research Institute, KFUPM. His research interests are centered on the development of solvent-minimized/greener analytical methods for trace and ultra-trace determination of emerging contaminants in environmental, food, and biological samples. He has published 25 papers in peer-reviewed journals.*

*Miguel de la Guardia is a Professor at Valencia University, has a 41 h-index and published 630 scientific papers,5 Spanish patents, 3 books on Green Analytical Chemistry (Elsevier, RSC and Wiley)2 books on Food analysis (Elsevier and Wiley) and 1 book on Air Analysis, has supervised 33 PhD thesis. Member of the Editorial board of Spectroscopy Letters (USA), Ciencia (Venezuela), J. Braz. Chem. Soc. (Brazil), Journal of Analytical Methods in Chemistryand Chemical Speciation & Bioavailability (UK), SOP Transactions on Nano-technology (USA) and Bioimpacts (Iran). Decorated as Chevallierdansl'ordre des PalmesAcadémiques by the Minister Council of France.*

*Jacek Namieśnik: Studies in chemistry at Faculty of Chemistry of the Gdańsk University of Technology (GUT). PhD in 1978, professor of analytical chemistry since 1996. From 1996 to 2002, and from 2005 to 2012 Dean of Faculty of Chemistry, Gdańsk University of Technology. Head of Analytical Chemistry Department (since 1995). Rector of Gdańsk University of Technology (2016- ). Chairman of the Committee on Analytical Chemistry of the Polish Academy of Sciences (2007-2015). Member of State Commission on scientific degrees and titles (2007- 2016).Major research interests included elaboration of new analytical procedures for determination of trace and ultratrace constituents in samples characterized by complex composition of the matrix, design and testing of specific (fit for purpose) analytical units and measuring devices, production of new types of matrix-free reference materials. Author and editor of 8 books, author and co-author of almost 750 papers published in international journals from the JCR list ($\Sigma$ IF $\cong$ 1 975,871) and over 400 lectures and communications published in conference proceedings, 19 patents and patents applications. Number of citations (without self-citations) =8177, h-index = 45 (from Web of Science, 06.12.2016). Supervisor or Co-supervisor of 60 PhD thesis (completed).*

*Marek Tobiszewski, PhD, works on environmental analytics, particularly determination of organic compounds in environmental samples. His research interests are also green chemistry, application of chemometric and multicriteria decision analysis techniques in optimization of chemical processes andsustainability assessments.*

**Keywords:** green chemistry • education • teaching methods • green chemistry metrics • educational tools

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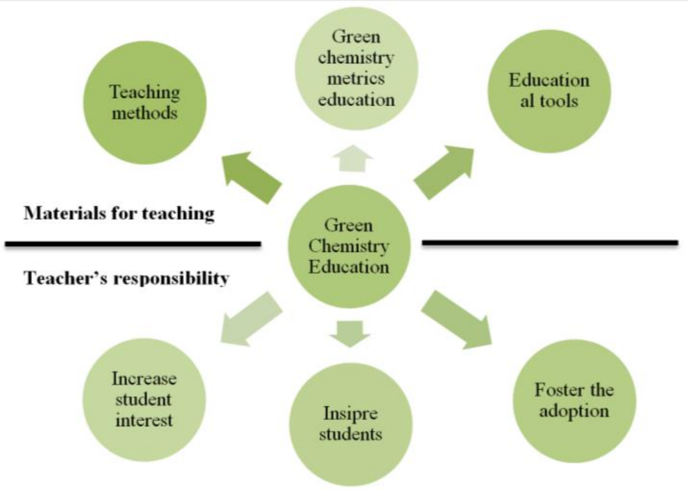


*Justyna Płotka-Wasylka*[a], Aleksandra Kurowska-Susdorf[b], Muhammad Sajid[c], Miguel de la Guardia[d], Jacek Namieśnik[a], Marek Tobiszewski[a]*

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