

Sustainable analytical chemistry—more than just being green*

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Abstract: This review article describes analytical chemistry beyond green chemistry and all efforts that contribute to a more sustainable development. A background is given on sustainable development and green chemistry. Examples of “greening” strategies for sample preparation, chromatography, and detection are given. Thereafter, the review discusses how and why a method or a solvent could be claimed as being “green”. Green metrics for analytical chemistry is discussed, including the environment, health, and safety (EHS) index and life cycle assessment (LCA). The choice of solvent and the criteria for a solvent being “green” is also discussed. Finally, sustainable analytical chemistry is described by considering the three important “legs” so as to obtain sustainable development—economic feasibility, societal relevance, and environmental soundness. Hopefully, the review article will stimulate some new perspectives on the difference between greenness and sustainability in analytical chemistry.

Keywords: green analytical chemistry; sample preparation; solvents; supercritical fluids; sustainable chemistry; sustainable development.

INTRODUCTION

Analytical chemistry plays an important role in the sustainable development of the planet. This is true not only for the monitoring of pollutants in the environment, but also for the development of more sustainable processes, as well as for supporting important areas such as improved uses of renewable materials and biorefinery solutions. Certainly, analytical methodologies should first of all hold high quality, such as being accurate, precise, and sensitive; and secondly, the method itself should be as environmentally sustainable as possible. However, the aim of this review article is to expand the current knowledge and thoughts about green chemistry, especially green analytical chemistry, to the more comprehensive field of analytical chemistry for a sustainable development, or “sustainable analytical chemistry”.

In this article, the author’s personal views on the role of analytical chemistry from a sustainable development perspective will be discussed taking cognisance of the significant work already achieved in the field. The review is certainly far from being a complete coverage of the subject, but rather contains snapshots of key contributions that the author has come across during the last several years.

Initially, a background on sustainable development and the current important questions in the green chemistry field will be given. Then green chemistry will be discussed, including the development of analytical chemistry in the area, as well as some useful tools that could be employed to assess the

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“greenness” of a process. Thereafter, the paper will focus on sustainable analytical chemistry and conclude with some suggestions for future research.

SUSTAINABLE DEVELOPMENT

Sustainable development is a concept that was established in 1987 by the World Commission on Environment and Development (WCED) through the well-known report *Our Common Future* [1], chaired by Norway’s prime minister at the time, Gro Harlem Brundtland. However, the awareness of pollution and environmental issues was raised long before then. For example, the unwrapping of the Minamata disaster in Japan 1956, where methyl mercury was released from a chemical company for over 20 years, resulting in the death of around 2000 people and severe neurological diseases in more than 10000 victims [2]. Perhaps most of us remember the start of environmental awareness from the 1962 book by Rachel Carson, *Silent Spring*, now published as a 40th anniversary edition [3]. Carson’s alarming observations were about the death of millions of birds due to environmental pollution, mainly pesticides such as DDT. During that time, industry dealt with air pollution by building taller chimneys, although obviously this would only protect the most nearby environment.

The second industrial revolution, during the second half of the 19th century, with innovations such as the steam engine and the combustion engine, resulted in a dramatic increase in the combustion of coal. In addition, the petroleum industry, starting in 1859 with the first oil well in Pennsylvania in North America, certainly was the start of our current oil-dependency, or fossil fuel-based economy.

In 1972, for the first time the United Nations (UN) gathered to discuss pollution and environmental challenges, which resulted in the report by Maurice Strong, which was also published in book form: *Only One Earth: The Care and Maintenance of a Small Planet* [4]. During this UN meeting, 113 countries were represented and the UN Environment Program (UNEP) was founded. Twenty years later, the UN Conference on Environment and Development (the Earth Summit) was held in Rio de Janeiro, Brazil. 172 countries participated, and several documents were published as a result. The documents include, for example, the Rio Declaration, Agenda 21, the Statement of Forest Principles, the UN Framework Convention on Climate Change (UNFCCC), and the UN Convention on Biological Diversity. The year after, in 1993, the International Organization for Standardization (ISO) formed the Technical Committee 207 on environmental management. ISO/TC 207 is the “umbrella” committee under which the ISO 14000 series of environmental management standards are being developed. These include, for instance, environmental management systems (EMS); environmental labeling (EL); life cycle assessment (LCA); and greenhouse gas management and related activities. These documents and their implications are important milestones in the work towards a more sustainable future.

In 1997, the Kyoto protocol was composed by the UNFCCC, with the aim to reduce greenhouse gases to fight global warming. Currently, 191 states have signed the agreement that went into force as of 2005. The only country that did not sign is the United States of America. Canada has since renounced the protocol.

Recently, in 2012, the UN again arranged a conference on sustainable development in Rio de Janeiro, Brazil. The meeting was popularly called Rio 20+ since 20 years have passed after the quite successful 1992 meeting. From a political point of view, the Rio 20+ meeting was not a success as only a rather vague document, titled *The Future We Want*, came out from the meeting [5]. However, several working groups had put extensive work into defining and elaborating around seven important focus areas:

1. Jobs: There are currently 190 million unemployed people.
2. Energy: There is a need to get away from oil-dependency.
3. Cities: The main challenges are congestion, pollution, housing, and transportation.
4. Food: There are 925 million hungry people today and many more expected in the future.
5. Water: Scarcity, poor quality, and inadequate sanitation will affect one in four people by 2050.

6. Oceans: Increasing temperature, decreasing pH, and pollution of our oceans affects drinking water, weather, climate, coastlines, food, and ambient air.
7. Disasters: Earthquakes, floods, droughts, hurricanes, and tsunamis are all devastating.

These focus areas are perhaps far from analytical chemistry, but as will be discussed further, chemistry and analytical chemistry are important factors for several of these areas.

GREEN CHEMISTRY

A literature search using the topic words “green chemistry” in Web of Knowledge, 2012-12-26, gave 8641 hits, of which one of the most cited (617 times) was published by Anastas and Kirchhoff in 2002 [6]. Paul Anastas is one of the key persons who first came up with the concept of green chemistry, which is about the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances [7]. Green chemistry includes both chemicals of immediate hazardous concerns and more global issues such as climate change, energy production, availability of clean water, food production, and the presence or spread of compounds of environmental concern. Green chemistry is simply a compilation of 12 principles that serve as a guideline to create more environmentally benign products and processes [6].

Green chemistry is about atom economy, energy efficiency, and avoiding the use of toxic substances. One obvious concern is the number of synthesis steps required to produce a chemical. In Jessop et al. [8], it was discussed how much energy was required and the release of CO₂ in the manufacturing of different solvents. The number of synthesis steps certainly affects the outcome, for instance, tetrahydrofuran (THF) costs about five times more in energy (MJ/kg) to manufacture than ethanol. In the same publication, it was also made clear that ionic liquids often require 20–30 synthesis steps, while hexane and CO₂ are available without any synthesis step (only purification/separation).

There are several excellent review articles describing the use of supercritical CO₂ (scCO₂) as a solvent in catalytic reactions [9], enzymatic reactions [10], extraction and fractionation [11], as well as processing of materials [12]. scCO₂ is certainly less toxic than hexane, but there are also other green solvent options, such as polyethylene glycol (PEG [13]), *d*-limonene [14], ethanol, and, of course, water. Some of the most enthusiastic researchers, and also pioneers in this field, are Roger A. Sheldon and Martyn Poliakoff, as they have further developed the principles of green chemistry. For instance, Poliakoff and coauthors described the 13 principles of green chemistry and engineering for a greener Africa [15], which are as follows:

- G – Greener Africa
- R – Regard for all life and human health
- E – Energy from the sun
- E – Ensure degradability and no hazards
- N – New ideas and different thinking
- E – Engineer for simplicity and practicality
- R – Recycle whenever possible

- A – Appropriate materials for functions
- F – Fewer auxiliary substances and solvents
- R – Reactions using catalysts
- I – Indigenous renewable feedstock
- C – Cleaner air and water
- A – Avoid the mistakes of others

Roger Sheldon has contributed strongly to the field of green chemistry through his work on the E-factor [16] and green solvents [17], which will be discussed further in the following sections. There is a lot more to say about green chemistry, but the reader is instead referred to any of the most recent

review articles on this subject, for instance, the one by Anastas and Eghbali [18] or in the special issue on green chemistry [*Chem. Soc. Rev.* Feb. 21, issue 4, 1405–1608 (2012)].

GREEN ANALYTICAL CHEMISTRY

To the best of my knowledge, it is Paul Anastas who first mentioned “green analytical chemistry” in a review article from 1999 [19]. However, analytical chemistry has been used since the 1960s to monitor pollutants from environmental and food samples. Analytical methodologies have continuously been improved by better accuracy, sensitivity, and precision. In addition, improvements have been done in terms of reducing the use of solvents in sample preparation and miniaturization of columns, however, not always mentioning the concept of green analytical chemistry. Green analytical chemistry is not about monitoring of environmental pollutants, but rather “greening of methodologies”. From the 12 principles, 7 principles of green analytical chemistry can be extracted:

1. Prevent or reduce the formation of waste, for instance, by using smaller inner diameter columns in chromatography.
2. Use less toxic/environmentally burdensome chemicals and solvents.
3. Design energy-efficient analytical systems and methodologies.
4. Avoid the use of chemical catalysts, derivatization reagents, and other auxiliary substances.
5. Catalysis is better than stoichiometric reactions.
6. In situ analysis is better than off-line analysis.
7. Use safer chemistry to prevent accidents such as explosions and fires.

There are several review articles [20–22] as well as a few books [23,24] describing the area of green analytical chemistry. For instance, Armenta et al. [20] described the time-line and concepts for many of the analytical techniques identified as being green, including microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), solid-phase microextraction (SPME), stir-bar sorptive extraction (SBSE), single-drop microextraction (SDME), and liquid–liquid–liquid microextraction (LLLME), among others. The focus has been on sample preparation, since this part of the analytical chain is well recognized as the least green, mainly due to the large consumption of solvents.

Greening sample preparation

In sample preparation, the solvent issue is obviously a main concern, and there are a large number of publications describing alternative extraction methods using pressurized hot (subcritical) water [25] and scCO_2 [26] as solvents. In some publications, different green extraction techniques have been compared [27]. In our own work, we have demonstrated that subcritical water enables a faster and greener alternative with equal accuracy compared to conventional solvent extraction, for the determination of flavonoids and anthocyanins in onion [28,29] and red cabbage [30]. In the case of quercetin in onion, we have conducted an LCA to examine the environmental impact of a novel method using hot water and thermostable β -glucosidase for the extraction and hydrolysis of quercetin glucosides in onion. The new method was compared to a conventional method based on the combined extraction and hydrolysis with aqueous methanol containing hydrochloric acid [29]. Figure 1 demonstrates the environmental impact of the two methods, as calculated in terms of primary energy consumption and CO_2 equivalents in the respective processes. The newly developed method clearly has less environmental impact.

Another sample preparation technique worth mentioning is SPME, which is based on the use of a sorptive fiber instead of an organic solvent. This fiber is immersed in the aqueous sample containing the target analytes. The technique was introduced by Janusz Pawliszyn in 1990 [31] and has grown and

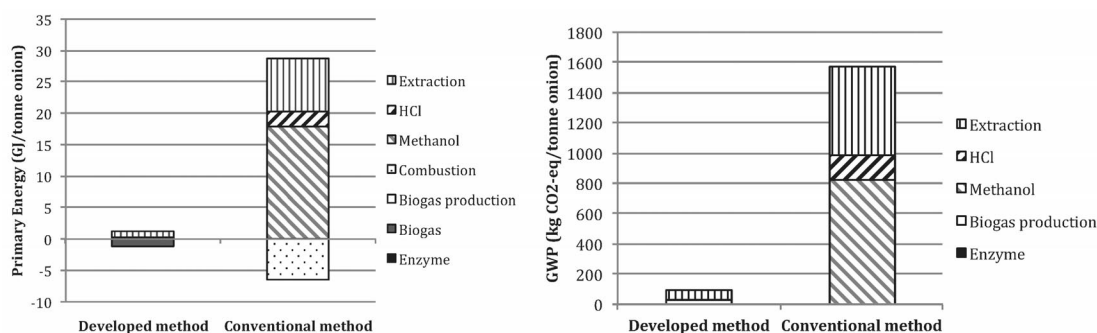


Fig. 1 LCA of a developed method based on pressurized hot water extraction at 120 °C and β -glucosidase catalyzed hydrolysis at 95 °C. Primary energy consumption (left) and global warming potential expressed as CO₂ equivalents. Figure modified from [29].

developed continuously since then [32]. There are now many different examples of sorptive extraction techniques that avoid or minimize the use of solvent. One such technique is molecularly imprinted solid-phase extraction (MISPE) [33], which is a more selective technique than SPME, and the principle of operation is more similar to solid-phase extraction. Briefly, a polymer is synthesized with a template molecule present, creating specific binding sites for the molecule. Even though in theory such a sorbent should be highly specific, it usually offers nonspecific binding as well, making the technique selective rather than specific. The challenge ahead is to make greener molecular imprinted polymers (MIPs) that could be easily cleaned and reused a large number of times.

Greening chromatography

There are several publications dealing with greening of chromatography, by using smaller separation systems [34], or greener solvents such as water [35,36]. In addition, “older” separation techniques such as gas chromatography (GC) and capillary electrophoresis (CE) are in fact quite green techniques, and when such techniques are applicable and practical to use, they are beneficial from a green chemistry point of view. However, not all compounds and complex sample matrices can be processed by CE or GC. Clearly, miniaturization is one way to go, and there is a lot of interesting novel research in microfluidics and lab-on-a-chip applications [37].

Another recent trend is that supercritical fluid chromatography (SFC) has been revived, and instrumentation is now available in both analytical and preparative scale from several vendors. Figure 2 shows that after 1990 there was a “dip” in terms of relative record count, comparing SFC with chromatography. However, SFC did not disappear completely and is now expected to get another upswing. What is different compared to the 1990s, is that there is less concern of whether the mobile phase is a supercritical fluid or not. Pressure, temperature, and co-solvent amount is optimized without considering the phase transfer into a liquid domain of the phase diagram. However, it has been shown that even though large volume-concentration of methanol is added to the pressurized CO₂, efficient chromatography is obtained with nice peak shapes. It is important to realize that the pressure needs to be high enough to avoid phase splitting into gas and liquid [38], unless this is desired, of course. The gain compared to conventional high-performance liquid chromatography (HPLC) is the speed and the lower volumes of organic solvents needed. Perhaps the biggest gains are found in applications where usually quite strong nonpolar organic solvents are used, such as those used in normal phase chromatography of lipids (e.g., dichloromethane).

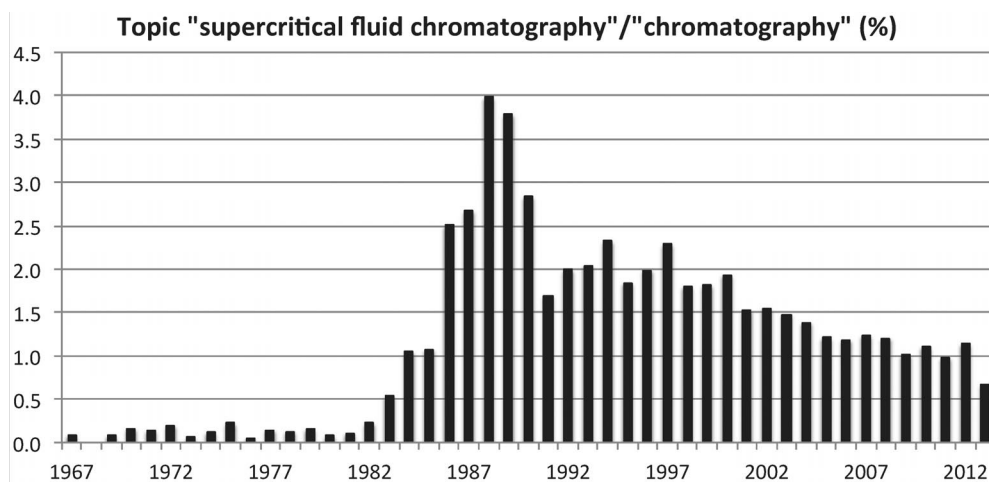


Fig. 2 Relative record count in percentage, using the topic SFC divided by chromatography, Web-of-Science 2014-04-25.

The use of pressurized hot (subcritical) water as a mobile phase in chromatography was pioneered by Roger Smith in 1996 [39]. Since then, there have been more than 400 published papers on the subject, including a recent review article that describes not only subcritical water chromatography but also ultrahigh pressure liquid chromatography and micro/nano-scale chromatography [36]. In one particularly interesting publication, pressurized CO_2 was added as a modifier to the subcritical water, in order to reduce the polarity of the solvent [40]. Results showed that the introduction of CO_2 at pressures of around 160 atm and temperature of 100 °C enabled Gaussian peak shape of 1-octanol and elution from a poly(styrene-divinylbenzene) column within 4 min. When water at 100 °C without the addition of CO_2 instead was used as a mobile phase, the peak was not eluting even after several hours. Similarly, benzene, toluene, ethylbenzene, and *p*-xylene gave retention times of less than 5 min when using 160 atm and 100 °C, compared to using only subcritical water at 200 °C when only benzene was eluting, after 30 min, see Fig. 3. However, it is unclear what the retention mechanism was, since CO_2 and

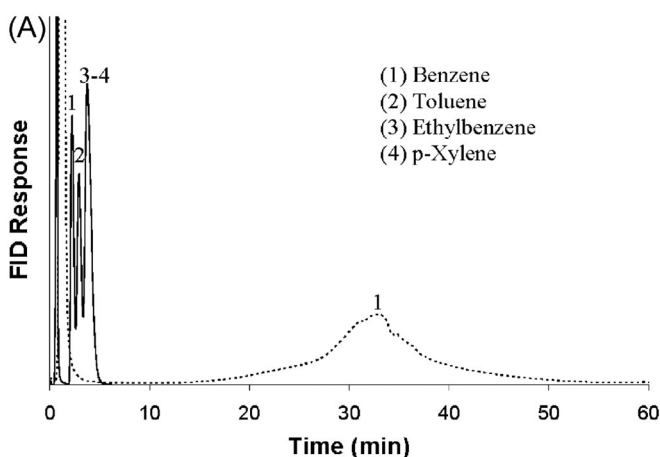


Fig. 3 Comparison of conventional subcritical water chromatography at 200 °C (dashed line) and CO_2 /water chromatography at 160 atm and 100 °C (solid line). Reprinted with permission from ref. [40]. Copyright © 2008, Elsevier.

water at those conditions are immiscible, giving carbonated water in equilibrium with a dense (CO₂) gas phase containing small amounts of water.

Greening detection

In terms of detection in analytical chemistry, most of the greening efforts have been focused on in situ analytical techniques, mainly different spectroscopic techniques [41]. From a green chemistry point of view, in situ analysis is beneficial because it allows for real-time assessment of a process, allowing for direct monitoring of the production of hazardous or non-safe substances. In situ analysis also avoids extra handling steps that usually lead to larger usage of chemicals and energy. An example of such a technique is Raman spectroscopy [42], which has been combined with microfluidic separation [43]. A clear advantage of Raman spectroscopy is the possibility to use it for in situ analysis in high-pressure fluid systems, since the laser beam reaches inside a fairly thick sapphire glass window [44]. For instance, we have demonstrated the feasibility of using Raman spectroscopy for solubility determination in scCO₂ [45]. Raman spectroscopy showed a great potential for use as an in situ monitoring detector, in processes, for surface analysis and for in vivo analysis in biological systems [46,47].

What makes it green?

Many of the publications already cited are well written when it comes to describing the different strategies in green analytical chemistry, however, the motivation around *why* a certain technique or method could be claimed as being green is rather weak. Often, common sense is sufficient, such as it is certainly better to use less solvent than more in an extraction step. However, the replacement of a quite toxic solvent with a less toxic one is perhaps not as clear, especially since different quantities of solvents are needed to achieve the same result. One of our approaches has been to replace hexane with hot ethanol in the extraction of carotenoids from carrot [48]. Our calculations showed that for the extraction of 1 g of β -carotene, 1.4 kg of ethanol at 60 °C was needed as a solvent, while approximately only 90 g of THF at ambient temperature was needed to achieve the same extraction, based on solubility data [49]. Hence, although THF was a significantly more toxic solvent, to both humans and the environment when compared to ethanol, a much smaller amount was needed due to the higher solubility of carotenoids in THF.

Clearly, there are many factors to take into consideration when “greening” analytical methods. Such factors include the amount of waste produced; toxicity and environmental burden of all chemicals used, waste generated; energy and electricity used in the analytical process, as well as in the production of the chemicals; and the safety of the analytical method. Analytical methods are not easily compared, taking all these factors into consideration. What is indisputably necessary in order to enable a comparison of different analytical methods is to use a defined functional unit, to which all methods can relate. Such a functional unit should preferably be “one analytical result”, taking the whole analytical chain into consideration, from sample preparation to data analysis. This means, for instance, that the volume of organic solvent used in method A could be compared to the volume of solvent used in method B, *per analytical result*. A functional unit enables a more holistic sustainable perspective, as described in more detail in the following sections.

SUSTAINABLE ANALYTICAL CHEMISTRY

It is becoming generally accepted that in order to claim the sustainability of a process or product, hard-core data on true environmental impact is needed. Hence, in order to fully assess the “greenness” of an analytical method, the environmental impact should be calculated based on input data that is as good as possible. There are several “green chemistry metric” tools to be used for calculation of environmental impact, including carbon footprint [50]; atom economy [51]; environmental E-factor [52]; environment, health, and safety (EHS) index [53]; and LCA [54,55]. Most of the green chemistry metrics was adapted

for classical green chemistry (i.e., chemical synthesis), however, these tools can still be used for the assessment of the greenness of the chemicals and solvents used in the analytical method.

Green metrics

In analytical chemistry, green metrics is rarely used. There are a few exceptions however. In Gaber et al. [56], an environmental assessment tool (EAT) was developed for HPLC methods using EHS data. The new software tool is called HPLC-EAT. HPLC-EAT was compared to another free software called the Eco-solvent tool for LCA of waste disposal options of distillation or incineration [57,58]. Such tools are valuable when choosing and developing analytical methods, in this case, regarding the selection of solvents for HPLC methods. In a similar study, an analytical method volume intensity (AMVI) green metrics tool for HPLC methods was developed, simply based on the total solvent consumption per chromatographic peak of interest [59]. In this case, no value was put on what type of solvent was used, but rather just the volume.

There is a national environmental methods index (NEMI) developed by U.S. government agencies and private sector organizations and companies in the United States. Current contributions by government agencies include the U.S. Environmental Protection Agency, the U.S. Geological Survey, and the U.S. Department of Energy [22]. The NEMI takes into account “PBT” (persistent, bioaccumulative, toxic, as defined by the EPA’s toxic release inventory, TRI); “hazardous” (as listed on the TRI); “corrosive” (pH during analysis is <2 or >12); and “waste” (the amount of waste generated in one analysis is >50 g). More than 800 analytical methods have been evaluated. The NEMI is a start, but a clear weakness is that it only considers the method as such and, for instance, not the energy demand for the manufacturing of the chemicals used. Similarly, physical, environmental, and health hazards data from the Globally Harmonized System of Classification and Labeling of Chemicals (GHS) have been used to create an “analytical eco-scale” system, utilizing penalty points for steps in the analytical method that does not comply with “ideal green analysis” [60]. Maximum obtainable points are 100, and any scoring above 75 is said to be green analysis. Again, a problem is the arbitrary scoring system, being at best semi-quantitative, which is also recognized by the authors.

The most powerful environmental assessment method is LCA, since this tool takes into account the total environmental impact from cradle to grave (e.g., the production of solvents, transportation, usage, and finally disposal of the solvent). There is only one example of an analytical chemistry study where LCA has been applied (in addition to the HPLC-EAT example above) for the comparison of preparative SFC to preparative HPLC [61]. In that study, depending on how the system boundaries were set, preparative HPLC required 26 % more resources than the preparative SFC separation due to its inherent higher use of organic solvents (process level boundary), while the opposite was true when using a larger overall industrial system boundary, due to the production of liquid CO_2 and the use of electricity for heating and cooling. For the critical mind, the results from an LCA strongly depend on the assumptions being made, in this case, one assumption was that liquid CO_2 was being produced with no other purpose, rather than being taken as a byproduct, for instance, from biogas production.

The case of greener solvents

One of the most difficult aspects to consider when comparing different analytical methods is the choice of solvent, both in sample preparation and in chromatography. First of all, as mentioned earlier, the solvent properties determine the solubility of the analytes as well as the selectivity of the process. Hence, a greener solvent could be worse because of the larger volumes required. There has been a lot of effort describing and classifying organic solvents. The easiest classification is based on the simplest intermolecular interactions—polar protic, polar aprotic, and nonpolar solvents. A similar classification is based on solvatochromic parameters [62], which contain the three Kamlet–Taft parameters α , β , and π^* , which quantify hydrogen-bond donating ability (acidity), hydrogen-bond accepting ability (basicity)

and polarity/polarizability, respectively. In Jessop et al. [62], solvatochromic data was published for 83 molecular solvents, 18 switchable solvents, and 187 ionic liquids that were cited in the green chemistry literature. In a related study by Jessop et al. [8], it was demonstrated by using the Kamlet–Taft parameters that there is a lack of appropriate green replacements for amines, hexamethylphosphoramide (HMPA), halogenated solvents, and aromatic solvents. In the same study [8], certain solvents were described as being green, including the Pfizer green list solvents (water, methanol, ethanol, 2-propanol, 1-propanol, 1-butanol, *t*-butanol, heptane, ethyl acetate, isopropyl acetate, acetone, and methyl ethyl ketone), two carbonate solvents (diethylcarbonate and propylene carbonate), two liquid polymers [poly(ethylene glycol) and poly(propylene glycol)], several CO₂-expanded solvents, scCO₂, subcritical water, and several biomass-derived organic solvents (γ -valerolactone, 2-methyltetrahydrofuran, glycerol, glycerol ethers, ethyl lactate, and cyclopentyl methyl ether). Ionic liquids were not included because of the generally large number of synthesis steps required to produce them.

A central question would be which solvents are actually green. Inherently, green metrics is needed to determine the greenness of a solvent. This was also pointed out by Jessop et al. [8], and some green metrics methods were suggested, such as calculation of the energy to manufacture the solvent; calculation of the cumulative energy demand from a life-cycle perspective; and assessment of the impact on health and the environment. An important aspect is whether it is beneficial from an energy point of view to incinerate the solvent after using it, or if it is worth it to recycle and reuse the solvent [58]. In Capello et al. [63], 26 organic solvents were examined in terms of their environmental impact from cradle (manufacturing) to grave (incineration alternatively distillation). LCA as well as EHS indexes were used to score the solvents, and the results showed that simple alcohols (methanol, ethanol) and alkanes (heptane, hexane) were environmentally preferable solvents from an LCA perspective, whereas the use of dioxane, acetonitrile, acids, formaldehyde, and THF would be less sustainable. When EHS aspects are also considered, methanol, ethanol, and methyl acetate seemed to be the preferred solvents, see Fig. 4 [63].

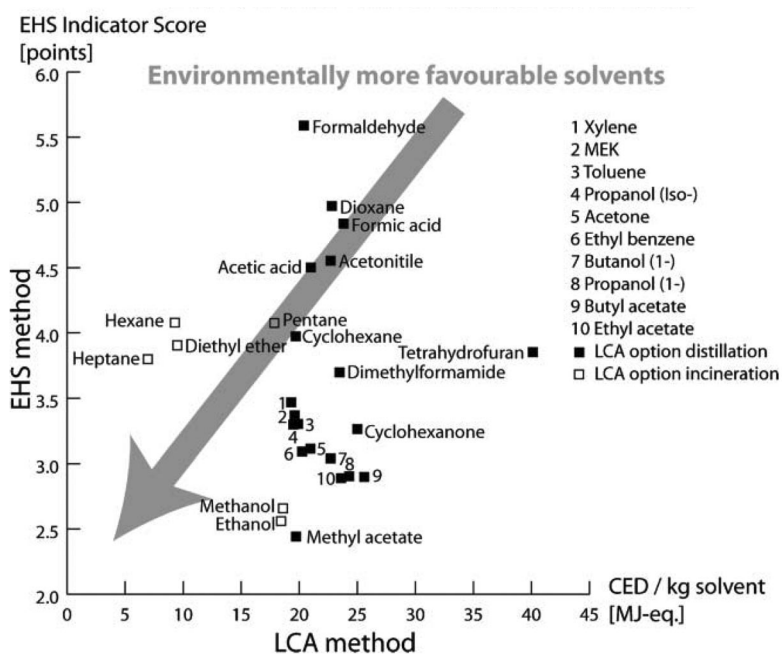


Fig. 4 Environmental assessment of 26 organic solvents using both EHS index and cumulative energy demand from manufacturing to waste handling. Reprinted with permission from [63]. Copyright © 2007, Royal Society of Chemistry.

It should be noted, however, that the study by Capello et al. [63] assumed that all solvents are manufactured from the petrochemical industry, although this is not always true for ethanol and methanol, for instance. In addition, water and pressurized CO₂ were not at all considered in the study.

How could this information be of interest to analytical chemists? A first thought could be that it is difficult to choose among organic solvents. One solvent that is more toxic than another one could be easier to evaporate, thereby consuming less energy. Such considerations would also depend on the general safety in the lab. Are there fume hoods? How is organic solvent waste handled? What is most important—cumulative energy demand or health aspects?

From green metrics to sustainability

It is well known that for a development to be truly sustainable, all three areas of environment, economy, and society need to be considered. So far, mainly the environmental aspects have been discussed, since they are the dominant ones in the green metrics tools. What could it imply to do sustainable analytical chemistry? Let us consider also economic and societal aspects.

For analytical chemistry to be economically sustainable, the methods should be cost-efficient, which often means high-throughput and fully automated systems. Portable devices that can be taken to the field for measurements at the source can be a cost-efficient alternative since sampling and transportation is minimal [64]. However, cost-efficient portable instruments do not always fulfil the expectations in terms of selectivity and limit of detection of the methodology.

Societal relevance implies that analytical chemistry should be developed in areas where there is a significant societal importance, including the creation of new job opportunities; energy efficiency and use of renewable resources; minimization of pollution in cities; food supply and security; water quality; oceans “health”; and prevention of devastating situations after natural disasters. Hence, for analytical chemistry to be sustainable for society, research efforts should go in those directions. This could imply anything from determining environmental effects of novel materials (e.g., nanoparticles in marine environments) or in situ assessment of reactions in biorefinery processes. Most of such relevant research questions require multi-disciplinary efforts, including natural science, social science, engineering, economics, and law. There are certainly examples of projects in analytical chemistry that deal with questions of less importance to the society. For sure, a crucial determinant here is the funding agency to select among research proposals in a sound and sustainable way. Again, this requires multi-disciplinary expertise, which in some cases can be a challenge.

Finally, analytical chemistry should be environmentally sound, which has already been discussed regarding waste minimization through, for instance, miniaturization; green solvents or solventless methods; energy efficiency; avoiding the use of auxiliary chemicals; preventing accidents through safer methods; and further developing in situ and in-field analysis techniques.

Another aspect to point out is that often larger-scale processes are developed from smaller-scale ones, hence it is important that although analytical methods are small-scale, they are sometimes taken to industry where the environmental impacts will be larger.

SUGGESTIONS FOR THE FUTURE

Future challenges in sustainable analytical chemistry are firstly to apply green metrics such as LCA and EHS to analytical methodologies, to assure a development towards environmental sustainability. Publication opportunities in this area are wide open, and this should be a trigger for researchers.

Secondly, it is important that analytical chemistry continues to take the lead in research questions of importance to the global society. It will be more and more important to be involved in interdisciplinary research projects. Such efforts facilitate thinking outside the box, which is indispensable for advancement in many of the large challenges we are facing.

Thirdly, some of those large challenges ahead of us, for instance, the transfer from fossil fuel-based economy to a bio-based economy, will require specific efforts in analytical method development. Another challenge to mention is the one of drug residues in the environment, in which research has shown that hormone-disrupting compounds are more toxic at extremely low concentrations than at relatively higher concentrations. This puts higher demands on the analytical methods. To tackle large challenges like these, and at the same time consider the greening of the methods, is probably the most challenging aspect of them all.

Finally, analytical chemistry must be recognized for being a crucial discipline of chemistry, pointing at the fact that analytical chemistry is not just a simple tool for other chemists to use, but a continuously developing research area with large implications for the future good.

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