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Article

Pedagogical Purposes of Scientifical and Technological Literacy within Sustainable and Green Chemistry in the High School

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Abstract: In this paper, a distinction is first made between environmental, sustainable and green chemistry; the last two are then examined in relation to the more general problem of the environmental education. A brief historical digression on the STS (Science, Technology and Society) movement tries to dissect the reasons why chemistry is seen by the general public as a problem, not as a decisive resource for the realization of the ecological transition. Although sustainable and green chemistry can be decisive in overcoming the insularity of chemical disciplines in the high school, it fails to effectively embed itself in educational practices. Specific operational goals, supporting a real scientifical and technological literacy in sustainable and green chemistry, can help chemical educators. They are provided at the end of an examination of the founding axes of sustainable and green chemistry, according to the criteria of scientific and technological literacy.

Keywords: green chemistry education; sustainability; scientific and technological literacy; science; technology and society; interdisciplinary studies; environmental education; chemical education

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1. Sustainable, Green and Environmental Chemistry

In chemistry, the ethical dimension is related to values guiding chemical research and chemists' public perception as scientists pursuing the common good. The way chemistry teachers promote ethical values in their chemistry classrooms, often in implicit ways, is decisive for the efficacy of sustainable development education [1].

Chemistry educators can play a fundamental role by helping students to understand, from a systemic point of view, how fields such as economics, politics, and law interact with natural sciences, in order to establish rational energy policies, to promote technological innovation, to reduce dependence on fossil fuels, and so on [2].

The branches of chemistry most suitable for the development of the necessary competences are "environmental chemistry" and the strictly related "green chemistry", because of their interdisciplinary nature and connections to the impact of humankind on the planet. Environmental chemistry is concerned with reactions in the environment and involves a study of the distribution and equilibria between components of an ecosystem [3], whereas green chemistry focuses on technological approaches to prevent pollution and to reduce the consumption of non-renewable resources [4].

Through environmental chemistry, the natural processes of Earth as well as the impact of human activities are studied; in the last few years the number of publications of this sector, also intended for general public, has been growing to raise awareness about pollution's consequences [5]. This kind of studies contributes in solving challenges related to food, energy, and natural resources [6]. Environmental chemists promote conservation and protection of the natural environment by monitoring sources of pollution and extent of contamination; they examine how chemicals interact with the environment, trying to forecast short-term and long-term consequences of such interaction.

Green chemistry is also called "sustainable chemistry", but some differences must be taken into account: whereas sustainable chemistry represents the "maintenance and continuation of an ecologically-sound development", green chemistry covers the "design, manufacture, and use of

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chemicals and chemical processes that have little or no pollution potential or environmental risk" [7]. According to previous researchers as Carra [8], sustainable chemistry is defined in an almost superimposable way to the definition of green chemistry ("sustainable chemistry is the design, manufacture, and use of environmentally benign chemical products and processes to prevent pollution, produce less hazardous waste, and reduce environmental and human health risks"); therefore, the term "sustainable and green chemistry" (SGC) will be used. Unfortunately, the communion between SGC and environmental education in the broadest sense is not taken for granted. In the next paragraph we will mention some issues involving environmental education and the Science, Technology and Society (STS) movement, and the difficult grafting of chemistry into them.

2. Environmental Education and Chemistry

For more than 30 years, more and more governments have introduced the environmental education in school syllabuses; this change occurred by introducing some learning objects in different single subjects or across disciplines. Another way was the implementation of optional environmental projects in schools. The environmental education has always presented problems related to its harmonization within science teaching. For example, in the 1980s, some authors observed that the barely dynamic nature of the relationship between teachers and students doesn't encourage debates during the science classes; it is well documented that the most frequent environmental education process was an education about the environment, neglecting critical skills development, because tried to avoid controversial situations in order to maintain discipline, or because they considered environmental issues too complex to be dealt with [9]. However, difficulties don't lie solely on teachers' attitudes: many students are unable to overcome their dependence to disciplinary knowledge and to discuss topics at very deep levels, being unfamiliar with open-ended tasks. Therefore, a gap between government requirements and real teaching practices has been detected, as demonstrated at primary level in the UK [10].

These problems are still present in many school contexts, representing a serious obstacle for an authentic environmental education, aimed at critical sensibility development. For example, the societal dimension of chemistry as it is taught in the schools needs further significant improvements [11].

To assure the interdisciplinary approach efficacy required by the environmental education, educators have to be flexible, abreast of teaching methods and adequately trained; some studies highlight a teachers' lack of interest and training about the environmental education [12]. Besides, some theoretical considerations point out the different nature of environmental and science education [9]: the main goal of the former is to strengthen some attitudes concerning environmental issues, whereas the latter aims at scientific mentality development. This distance can be explained as a residual of the positivist idea of science, opposed to a more social vision of it. Some studies tried to conciliate these opposite visions, starting from the Klopfer's taxonomy of the outcomes in science [13]. At the highest levels of his classification concerning the "Orientation" it is possible to read:

- historical perspective: recognition of the background of science;
- realization of the relationships among science, technology and economics;
- awareness of the social and moral implications of scientific inquiry and its results.

Klopfer's classification has been important to nourish the STS movement, based on the transformation of the traditional disciplinary science teaching into a general scientific literacy centered on the resolution of social problems. Although formulated in the 1970's, it continues to be considered by several researchers, for example in examining high school students' attitudes toward science using TOSRA, the Test of Science Related Attitudes measuring students' attitudes toward science in seven categories (Social Implications of Science, Normality of Scientists, Attitude toward Scientific Inquiry, Adoption of Scientific Attitudes, Enjoyment of Science Lessons, Leisure Interest in Science, and Career Interest in Science) [14].

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What is the role of chemistry? Students' improvement in dealing with environmental issues within chemistry lessons leads not only to a better understanding of general chemistry but also to well-developed environmental attitudes, as shown by the report of the NEETF survey in the USA [15]. As above specified, the contribute of SGC is essential to implement a real environmental education, at the same time helping to abolish chemistry curriculum isolation.

A detailed analysis of 143 papers about the incorporation of green chemistry into chemistry teaching has focused on: learning subjects, curriculum, integrative contents, context, other education environments, use of instructional materials, and comparison between green chemistry and "traditional chemistry" [16]. Most proposals focus on the learning subject, followed by curriculum discussions and integrative contents. Several papers brought aspects related to the systemic vision for the interconnection of green chemistry with sustainability issues, revealing a new methodological challenge by proposing integrative content as teaching strategies. Despite their good intentions, most teaching experiences and intervention proposals still remain attached to occasional and poorly evaluated events [16]. Nevertheless, the road is traced: from chemistry community *mea culpa* to the emergence of chemical sustainable practices and technical innovations materializing chemists' ethical commitments [16]. The hope is the diffusion of a new image of the professional chemist, ethically committed to the protection of the environment.

3. STS Movement and Chemistry

In order to understand the STS movement, a short science teaching historical perspective is presented [17]. At the beginning of the 19th century, scientific knowledge was divided into two components: applied sciences (such as engineering or medicine) and "pure" sciences. Applied sciences were oriented to action, realizing projects in a particular social context, whereas pure sciences represented the paradigm of the scientific knowledge in the strict sense. Initially this separation influenced the educational policies of higher-level institutions: engineering or medical faculties were called "schools of applied sciences", while physics and chemistry were united within the faculty of sciences. Secondary school science teaching was organized for the most part according to pure sciences landmark. So, although teaching profession is practiced in a human and social complex context as that of the engineers or physicians, sciences are taught according to standards deprived of the complexity of human relationships. All these factors caused a gradual depletion of efficacy of science education.

The STS movement provided a response to science teaching weakening, even if the persistence of the traditional disciplinary method is still used producing discouraging results: in particular in industrialized countries, students are not interested or are even hostile towards sciences for at least thirty years [18], as denounced by international organizations such as UNESCO [19]. This crisis affected the number of scientific careers, putting scientific and economic development in danger, as the Rocard Report demonstrate [20]. In particular, there is a shortage of skilled chemistry professionals [21].

It is possible to differentiate two schools of thought in the STS movement. The first one is characterised by a great faith in scientific progress as a mean to guarantee a better future; therefore, science teaching should train young people to respect nature and properly operate on it. Many teachers supporting this school of thought attribute a great importance to political and ethical issues, in particular to ecological concerns and public health problems [22]. Such a way of thinking, influenced by the scientism [23], can be considered a sort of prolongation of the Enlightenment era. Serious environmental problems and diseases, mostly due to large-scale dangerous chemicals production from the 1960s, undermined this confidence in scientific achievements.

The second school of thought is based on the analysis of social and economic components; depending on this analysis, the above mentioned "scientific literacy" is necessary to equip people with cultural instruments capable of guiding them in a complex world. This line of thinking is known as STL, "Scientific and Technological Literacy", or AST, "Alphabétisation Scientifique et Technique" (because of its special resonance in France). According this current, modern science does not produce absolute truths: it is an efficient way to approach knowledge [24]. This conception abandons

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positivistic influences, being in line with Thomas Kuhn's theories about the nature of science; according to them, science is a relativistic and social construction. Kuhn's studies influenced learning theories, causing the rise of constructivism [25]. Constructivism and the idea of scientific literacy process reinforced a more democratic vision of science education, not confined to future scientific professionals but to all citizens. By this inclusive science education process, all citizens should develop skills and attitudes towards scientific and technological issues. A widespread scientific awareness is considered an important factor to assure the survival of democratic process according to scientists such as the Nobel Prize for chemistry Roald Hoffmann (1937-) [26]: according to him, the inadequate public understanding of chemistry is a barrier for the full realization of democracy.

STSE (Science, technology, society and environment education) originates from the science technology and society (STS) movement in science education, emphasizing the environmental education and the role of students: they are encouraged to engage in issues pertaining to the impact of science on everyday life and make responsible decisions about how to address such issues [27,28].

However, especially in developed countries, the sciences - and chemistry in particular - do not enjoy a good reputation. This hostility is combined with a sort of delegation to the so-called "experts" on environmental issues; gap between northern and southern countries is particularly accentuated for chemistry [29]. With good probability, students' perception of a discipline such as chemistry is conditioned by a general negative consideration because of the pollution caused by large-scale production of chemicals. Therefore, in order to examine the peculiar situation of chemistry is necessary to fully understand students' disaffection toward this discipline by a historical approach, as later reiterated.

4. Scientific and Technological Literacy Goals of Green Chemistry

The main aims of STL (or, on the whole, of STS/STSE movement) concern three different dimensions: political-economic, social and purely cultural [17].

Because of the crisis of scientific teaching - chemistry in particular – and the too slow green chemistry rooting in the educational world [16], it is appropriate to define these three dimensions for SGC, in particular for high school level, a significant turning point of: future career choices [21], public understanding of chemistry and its importance for ecosystem preservation [30].

4.1. The Political-Economic Axis

The political-economic axis lies on the belief that a lack of scientific and technological literacy could cause a dangerous moving back of developed nations (that is connected with the scientism's current above-mentioned).

Rising of SGC has been described as some sort of revolution, like the agricultural and industrial revolutions that characterized periods in previous centuries. SGC is very integrated within chemistry itself and cannot be treated as a separate discipline; that mainstream nature of SGC may mean that in years to come it will simply be absorbed into the normal business of what we call chemistry [31]. There are several drivers for change towards SGC; the specific drivers and their relative importance are certainly situational and often their influence is interconnected. Clark [32] described and analyzed several key drivers in detail, showing how they stem not only from environmental issues, but also from economic and social factors.

4.2. The Social Axis

The social axis is based on the idea of democracy maintenance; for example, democratic governmental choices about usage of food additives or pesticides suppose public debates with the participation of informed people. Hoffmann [26] highlighted the importance of correct and complete information from chemists, fearing the danger of ever greater hostility towards synthetic products, in the common imaginary always and in any case harmful. One of the remedies proposed by Hoffmann [26] consists in a different approach from chemists, more sympathetic towards the layman, using forms of communication that induce the ordinary citizen to more rational and cautious

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considerations. SGC education could be a royal road for a better "social reception" of chemistry, finally rehabilitated in the eyes of the general public. This is important in order to counteract the chemophobia, according to which everything "chemical" is a source of danger, while everything "biological" is good and positive [33].

4.3. The Cultural Axis

The third axis, purely cultural, is founded on the value of technical and scientific knowledge as patrimony to be shared with other people and source of life's pleasure. That suggests two important dimensions, related to history and epistemology.

4.3.1. Historical Dimension

As pointed out, damage due to the intensive production of chemicals was highlighted from the 1960s, causing a progressive loss of faith in science in the society. It is possible to establish a precise year as reference point for this phenomenon: the publication of "Silent Spring" [34] by Rachel Carson (1907-1964), which brought the environmental impact of synthetic pesticides to the attention of the American public. Most chemical companies rejected Carson's reports, but her message nonetheless spurred action initially at national, then at international level: a general renewed environmental awareness led to the formation of the U.S. Environmental Protection Agency (EPA). Many pesticides were banned or their usage was restricted, in particular DDT (that gained popularity after its use during World War II to prevent the spread of diseases as typhoid and malaria).

Carson explained how insecticides can kill birds that feed on insects harmful to plantations, moving through the food chain and the natural environment, causing immediate and long-term consequences. She carried out very extensive researches, studying dozens of reports and interviewing experts; her purpose was not to ban all the chemicals used in agriculture, but to understand the risks to human health and environment and to evaluate other products usage or biological alternatives [35].

After the publication of the book, a virtuous process began among professional chemists as well, focusing on more sustainable practices. Even now, "Silent Spring" is universally considered a text that changed the world: it suggested a needed change in how democracies operated, in order to allow individuals and groups to question governments' environmental choices.

The Carson's report became known worldwide, therefore chemists' awareness about the impact of chemical products slowly increased towards the development of new areas of research dedicated to the study of the environmental equilibriums (environmental chemistry) and of their maintenance in coexistence with the production and usage of chemicals (SGC). The first important environmental chemistry publications about natural waters [36] and atmosphere [37] appeared in the 1970s, whereas Paul Anastas (1962-) coined and defined the term "green chemistry", launching the first research program in the field and co-authored a ground-breaking book in which the "12 Principles of Green Chemistry" were outlined [38]. Thirteen years later he wrote about the goal of chemistry community: to design chemical products and processes that reduce or eliminate the use and generation of hazardous substances [39].

A more careful study shows that SGC has many origins, depending on the country considered: for example, EPA researchers were driving forces in the formation of this new field in US, whereas in UK the deteriorating public image of chemistry was decisive; in the Netherlands, the search for renewable resources and raw materials mostly guided the process [40].

Although green chemistry was officially born in recent times, in reality its premises are much more distant in time. A significant example is given by the researches of Giacomo Ciamician (1857-1922) in the field of photochemistry [41].

4.3.2. Epistemological Dimension

This dimension makes possible to understand how science is structured and how scientists contribute to its construction. As far as SGC is concerned, it is important to highlight its distinction

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with respect to environmental chemistry, as specified in Paragraph 1. However, it is also necessary to identify the commonalities between these two fields, especially in relation to a particular field of application: safety

The environmental chemistry role has been increasing worldwide because the growing pressures to protect the human health from exposure to hazardous chemicals [42]. The resulting chemical industry legislation may be the ideal basis for the development of green educational programs [43].

Balaban and Klein [44] have proposed a partial ordering of sciences, in which chemistry may be argued as being the "central science", but the relationship between chemistry and law, economics and ethics is a distant one. Such a relationship should play a larger role in education, so that the central role of chemistry in society can become clearer. The link between environmental/SG chemistry and legislation in the field of safety offers an excellent example of the particular proximity of chemistry to other fields of knowledge.

The ability of teachers to describe and explain features of interdisciplinary and systemic view of chemistry (including environmental aspects) and the related use in teaching practice seems broadly positive regardless of their differences in background [45].

4.3.3. Aesthetic Dimension

The aesthetic dimension leads to the appreciation of how nature and machines work, experiencing the related sense of beauty. In relation to the synthesis of chemicals according to green chemistry procedures, there is an additional element of attraction for chemists: a pursuit of practical elegance where the core principles of green chemistry are used in developing a synthetic strategy [46], for example by catalysis [47]. SGC is applied also in cosmetic sciences [48]. Furthermore, cross-disciplinary fields are realizing the communion between art and SGC, combining ethical and aesthetical values [49].

4.3.4. Corporal Dimension

The corporal dimension allows us to perceive technological tools as a particularity of the human intelligent nature. Solar batteries or lithium batteries are good examples of technologies that are now part of our daily lives, as are catalytic converters or environmentally friendly building materials. Another example is constituted by the photosynthetic glass [50] aimed at realizing the artificial photosynthesis, considered the Holy Grail of sustainability [51].

4.3.5. Communication dimension

Science contributes to shape a shared view of the world. Investments and dissemination on the importance of green chemistry and how they affect our health and environmental sustainability are extremely important for the process of future improvements: SGC has multidimensional impact; unfortunately, most people don't believe that the chemical industries are concerned about the development of sustainable actions [52], whereas the chemophobia is widespread [33].

4.3.6. Pragmatic Dimension

This dimension is related to practical needs. For example, it is necessary to know the mode of operation of the devices used, as well as the effect of specific nutrients on the organism, or how to prevent particular diseases. In this regard, the integration of SGC into toxicology curriculum is very significant; that allows an increased concern over the chemical safety, a particular awareness of chemical hazards, and a greater readiness on how to avoid or minimize chemical exposure potential in certain situations [53,54].

5. Sustainable and Green Chemistry Pedagogical Ends

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After listing the above-described general purposes, some pedagogical ends can be specified [17] fitting SGC contents: personal autonomy, development of communication skills, range of action enlargement.

a. Personal autonomy

To be informed about the reasons of some practical precautions, expedients or adaptations promotes individual autonomy. Still in the toxicology field, you need to know how to look for hazard information examining the Safety Data Sheets, SDSs [53], or the hidden dangers of vitamin-fortified products with associated health-benefits claims: an examination of toxicity of vitamins demonstrates that "the dose makes the poison" [53]. In general, autonomy in searching for information can be considered the main goal of scientific literacy at all levels.

b. Development of communication skills

The ability in expressing mental representations about scientific issues allows us to tell others our ideas on the subject, making negotiation possible within political or ethical debates. For example, it is possible to read, in contrast with the mainstream, that plastics are usually the greenest choice because it reduces waste production and greenhouse effect in comparison with other materials; besides, microplastics could absorb pollutants in seawaters, protecting us against illness [55]. In order to support this position, it is necessary to be well versed in scientific literature, to know how to argue and interpret the available data, comparing them with those demonstrating the opposite theses.

c. Range of action enlargement

Science is intrinsically connected to power: an individual characterized by autonomy (a.) and communication skills (b.) has the possibility to enlarge his range of action. This can happen on an individual level, with more or less limited repercussions, or collectively, when top positions are assumed in the associative and/or professional fields. In the first case, within safety legislation, single individuals can be involved actively as Downstream Users (DU). All chemicals must be trademarked and analyzed by the manufacturer, who must inform the European Chemicals Agency (ECHA) of the chemical properties and the safety procedures. Information about any hazards is provided in SDSs. Information transfer goes not only from Manufacturer/Importer (M/I) to DU but also from DU to M/I by the SDS. DU must communicate to manufacturer how they use the chemical product and the context of its use (if this information is not reported on SDS); in such a way, the new use could become an "identified use" with a known "exposure scenario", in case of health or environmental problems have been excluded. Schools must get involved too: there is a growing need to apply concretely sustainability issues by safety issues and legislation [43].

5.1. Operational goals

Operational goals provide teachers with precise indications about teaching practice. STL operational goals are reported with reference to SGC. Students have to be able to….

…. consult experts: in order to understand speeches coming from different experts (physicians, engineers, computer technicians...) finding an equilibrium between the limits of one's own knowledge and the critical sensibility exercise toward experts' words. For examples, chemists and geologists can suggest a particular site to be used as landfill; informed citizens should express favorable/unfavorable opinions in a reasonable and respectful way.

… represent simple models: scientists consider simple models highlighting their imperfection in comparison with the real phenomenon they want to describe. Applied sciences tend to consider simple models taking into account their efficacy within a practical application. It is important to develop students' competences in conceiving simple models and to use them in a particular context of action or communication. Representing a fuel cell in a simple way allows students to understand its working principles, whereas a complex cell model can discourage its use in a real context.

… use black boxes: in daily life you need to handle different type of devices, instruments or chemicals without necessarily knowing their inner composition (for example, to be informed about the reasons to swallow drugs in the right way, without knowing their complete chemical composition). In some cases, there is the need to understand when it is necessary to open a black box, for example in managing a photovoltaic system.

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… use metaphors: employing analogies to understand science concepts doesn't correspond to a loss of rigor in describing scientific concepts. After all, scientific concepts are fully-evolved and standardized metaphors. Especially in a secondary school chemistry course, metaphors can be very useful in order to approach the working principles of a green technology, such as the use of sustainable biopolymers for soil properties enhancement [56].

… develop interdisciplinary knowledge: concepts such as clean energy deserve interdisciplinary explanations. Non-scientific disciplines should participate in the interdisciplinary teaching as well, avoiding misrepresentation or underrepresentation of science key concepts. A change of consciousness is needed starting from the reduction of the distance between humanities and scientific culture, unfortunately still alive despite the numerous interdisciplinary research fields now established as ecological humanities [57].

… know standardized languages, scientific models and techniques: since SGC is very integrated within chemistry itself [31], STL would not be possible without referring to standardized languages, techniques and models of chemistry. Concepts such as mass, weight, electrical charge or chemical reactions require standardized points of references to make their use possible in the community.

…negotiate not only with people, but also with regulations, things and techniques. Some examples: to consider the quality/price ratio of a commercial product, to respect terms for the realization of technical operations, to know rules and regulations within any science-related business. Concerning the quality/price ratio, a good example is provided by cat litters: synthetic silica gel cat litter is harmless compared to clay litter, wrongly considered "ecological"; actually, clay litter is commonly produced in an environmentally degrading process using strip mining, that removes the surface layer of the soil undermining its fertility almost irreversibly [45].

…translate: it means to move without effort from a level to another, changing perspective from time to time. So, "salty water" will be, in chemical language, "saline solution", better still if the name of the salt and its concentration are specified. Many specific terms refer to SGC: an example is the "E factor" [58].

…be decision-makers. STL is realized if it provides tools to decide in technical, political or ethical fields by gathering up the scientific notions assimilated. A real ecological transition will not be possible without the conscious use of the vote by citizens.

… identify a debate as technical, political or ethical. Technical debates are finalized to action; ethical debates try to define the purpose of the action by taking into account the values implied; political debates find possible compromises between groups with different opinions. It is important to recognize these three dimensions in order to take an active role in the decision-making process. The historical axis can teach about past debates carried out incorrectly, without respect for scientific data: a very significant example is given by the story relating to Rachel Carson; she was well-equipped for the task of writing "Silent Spring", but industrial chemists attacked her. Unable to find errors in her work, some powerful industrial groups distributed publications that resorted to unsubstantiated claims of scientific inaccuracy, condemnations of emotionality in her work, and attention on the benefits of their own products [59].

6. Conclusion

Chemistry has taken on a crucial role in science and society. As the central science, it also is at the heart of many areas that are not necessarily labeled "chemistry. In earth science, pharmacy, medicine, agriculture, nutrition, and environmental science the practice of chemistry has a profound influence. Our appetite for materials and energy is increasing faster than our ability to meet demands: there is no easy way to solve this problem. SGC offers a step in the right direction, but it cannot penetrate effectively in education system, getting STL goals in a capillary way. This article offers a short list of tools in order to identify different foundational axis of SGC within STL, and provide some operational goals useful for chemistry educators.

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