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High School Sustainable and Green Chemistry: Historical–Epistemological and Pedagogical Considerations

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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 environmental education. A brief historical digression on the Science, Technology, and Society movement attempts to dissect 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 high school, it is not well-embedded in educational practices. This situation is slowly changing thanks to the implementations of systems thinking in teaching practice, showing interconnections between the molecular world and sustainability. Historical and epistemological studies provide an all-encompassing framework for the relationship between chemistry and the environment in a broad sense, giving a solid foundation for educational projects. Specific operational goals can help chemical educators in supporting real learning, as well as an examination of the fundamental axes of sustainable and green chemistry, according to the criteria of Scientific and Technological Literacy. Finally, the results of some research carried out in secondary school are presented. These results demonstrate the effectiveness of the interdisciplinary-systemic approach in teaching chemistry as well as in guiding future green careers and reducing the gender gap, preparing high school students in the best possible way to face the challenges of an increasingly interconnected and complex world.

Keywords: green chemistry education; sustainability; scientific and technological literacy; science; technology and society; interdisciplinary studies; systems thinking; environmental 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 how fields such as economics, politics, and law interact with natural sciences, in order to establish rational energy policies, promote technological innovation, 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 strictly related "green chemistry", because of their interdisciplinary nature and connections to the impact of humankind on the planet. Environmental chemistry concerns reactions in the environment and involves the study of distribution and equilibria among the components of an ecosystem [3], whereas green chemistry focuses on technological approaches to prevent pollution and 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 in this sector also intended for general public has been growing, to raise awareness about pollution's consequences [5]. These kinds of studies contribute 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 the extent of contamination; they examine how chemicals interact with the environment, trying to forecast short-term and long-term consequences of such interactions.

Usually, 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 chemicals and chemical processes that have little or no pollution potential or environmental risk" [7]. At the end of the 1990s, researchers such as Carra [8] defined sustainable chemistry in a way similar to 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"). In more recent times, this distinction has been clarified, for example, by a list of criteria categories to meet the definition of sustainable chemistry [9].

Moreover, historical research contributed to distinguishing these two fields. According to Krasnodębski [10], the history of green chemistry has garnered attention from scholars in the history of science, social sciences, and STS (Science, Technology and Society) studies, whereas the history of sustainable chemistry is largely untold. Historians of science and STS scholars play a key role in contextualizing and historicizing the relevant terminology [10].

However, this article refers to both domains, so the term "sustainable and green chemistry" (SGC) will be used. Unfortunately, the communion between SGC and environmental education in the broadest sense is not to be taken for granted; actually, it presents considerable difficulties. In order to analyze this problematic relationship, some issues involving environmental education and the STS movement will be mentioned, highlighting the difficulty of grafting chemistry onto them.

2. Environmental Education and Chemistry

For more than 30 years, more and more governments have introduced environmental education in school syllabi; 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. 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 does not encourage debates during science classes [11]; it is well-documented that the most frequent environmental education process was education about the environment, neglecting critical skills development, because teachers tried to avoid controversial situations in order to maintain discipline, or because they considered environmental issues too complex to be dealt with [12]. However, difficulties did not lie solely in teachers' attitudes, because of the inability of many students in overcoming their dependence on disciplinary knowledge and discussing topics at very deep levels, being unfamiliar with open-ended tasks [13–15]. Therefore, a gap between government requirements and real teaching practices has been detected at all levels in several countries. In order to improve the efficacy of education projects about environmental issues and science-related contents, discussions between teachers and researchers during implementation phases represent a key strategy [14].

Problems highlighted are still present in many school contexts, representing a serious obstacle for authentic environmental education, aimed at critical sensibility development. For example, the societal dimension of chemistry as it is taught in schools needs further significant improvements [16]. Many studies at the international level demonstrate that chemistry is unpopular among students, as revealed by The Relevance of Science Education (ROSE) project [17]. ROSE's purpose was to analyze information on 15-year-old learners' attitudes towards science and technology, and feelings with regards to environmental challenges. The ROSE report showed clearly an overall pattern in which pupils from developing countries express the highest interest in science and a certain mistrust in their ability to have a direct impact on the resolution of environmental problems. Whereas the sense of discouragement regarding possible remedies for environmental degradation unites students either from developing areas or from industrialized countries, the gap between northern and southern countries is particularly accentuated in relation to the interest in chemistry; it is no coincidence that there is a shortage of skilled chemistry professionals, especially in developed countries such as the US [18,19]. Moreover, the ROSE report shows that the gender gap is more marked in industrialized countries, where girls are less interested in subjects such as chemistry than boys.

High school serves as a significant turning point of future career choices. Self-efficacy in task-oriented and chemistry learning aspects is the driving force of choosing a chemistry career. Therefore, it is important to enhance students' choice in chemistry-related careers via quality educational programs [19]. Appropriate career-related instruction, implemented during high school chemistry lessons about environmental issues, influences students' career awareness and their interest towards science learning [14].

Although individual case studies cannot be generalized [20], there are now numerous qualitative and quantitative investigations demonstrating the effectiveness of collaboration between high school teachers and academics in implementing educational projects about environmental issues and chemistry-related topics; several examples are provided by the socio-critical and problem-oriented approach to chemistry teaching [21], aimed at promoting higher-order cognitive skills (HOCSs) such as communication, reflection, evaluation of controversial issues concerning environment, and public health. Such projects need an interdisciplinary approach, requiring flexible educators who are abreast of teaching methods and adequately trained. Of course, teachers' interest is a key factor; some studies highlight teachers' lack of interest and training about environmental education [22]. Some theoretical considerations pointing out the different nature of environmental and science education [12] could help understand these data; 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, as opposed to a more social vision of it. Some studies have tried to reconcile these opposite visions, starting from Klopfer's taxonomy of outcomes in science [23]. At the highest levels of his classification concerning "Orientation", one can read the following:

- 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 for nourishing the STS movement, based on the transformation of traditional disciplinary science teaching into a general scientific literacy centered on the resolution of social problems. Although formulated in the 1970s, it continues to be considered by several researchers, for example in examining high school students' attitudes toward science by TOSRA (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) [24].

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 (National Environmental Education and Training Foundation) survey in the USA [25]. The contribution of SGC is essential for implementing real environmental education, at the same time helping to abolish chemistry curriculum isolation. Unfortunately, there is still a long way to go. 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" [26]. Most proposals focus on the learning subject, followed by curriculum discussions and integrative contents. Several papers presented aspects related to systemic vision, in order to interconnect 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 proposals still remain attached to occasional and poorly evaluated events [26]. Nevertheless, the road is traced from chemistry community mea culpa to chemical sustainable practices and technical innovations materializing chemists' ethical commitments [26]. The hope is the diffusion of a new image of the professional chemist, ethically committed to environmental protection.

3. Literacy in Sustainable and Green Chemistry: Pedagogical Purposes and Operational Goals

The above-mentioned STS movement had a very important role in renewing chemical education. In order to understand that, a short historical perspective is presented. 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 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 the pure sciences landmark. So, although the teaching profession is practiced in a human and social complex context as that of 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 [27].

The STS movement provided a response to the weakening of science teaching, even if the persistence of the traditional disciplinary method is still used, producing discouraging results; in particular, in industrialized countries, students are not interested [17], or they are even hostile towards sciences, the state of affairs for at least thirty years [28], as denounced by international organizations such as UNESCO [29]. This crisis affected the number of scientific careers, putting scientific and economic development in danger, as the Rocard Report [30] and the lack of chemistry professionals demonstrate [18,19].

It is possible to differentiate two schools of thought in the STS movement. The first one is characterized by a great faith in scientific progress as a means 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 [31]. Such a way of thinking, influenced by scientism [32], can be considered a sort of prolongation of the Enlightenment era. Serious environmental problems and diseases, mostly due to large-scale dangerous chemical 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, considering scientific literacy 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 to this current of thought, modern science does not produce absolute truths; it is an efficient way to approach knowledge [33]. This conception abandons positivistic influences, being in line with Thomas Kuhn's theories about the nature of science, for which scientific knowledge is a relativistic and social construction. Kuhn's studies influenced learning theories, causing the rise of socio-constructivism [34]. Social constructivism, and the idea of scientific literacy for all, reinforced a more democratic vision of science education, not confined to future scientific professionals only. By this inclusive science education, all citizens should develop skills and attitudes towards scientific and technological issues.

In secondary school, however, the tendency has been to focus only on teaching scientific representations as truths, but scientific results are not definitive or absolute; they are often presented without mentioning why some scientists consider fruitful some specific representations instead of others. Scientists' choices about their practices, as well as the social shaping of scientific knowledge, are concealed, thus inducing a belief that the current scientists' view of the world is the only one possible [35].

The use of disciplines has proved to be a remarkably powerful approach. Traditional science teaching is disciplinary; nevertheless, "real" problems can hardly be broached in a pertinent way by one discipline only. In order to use an interdisciplinary approach in teaching, Fourez [35,36] coined the term "islands of interdisciplinary rationality". The image of an island evokes a representation emerging from an ocean of ignorance, because fairly limited knowledge can adequately illuminate a situation, although to answer in a definite and complete way complex questions is of course not possible, especially in a school context. Nevertheless, students' representations are intended to allow discussions and negotiations, that is to say, promote rational attitudes.

In order to better direct teachers' action within these islands of rationality, Fourez has also proposed some pedagogical ends concerning personal autonomy, development of communication skills, and range of action enlargement [27] (Figure 1). Such purposes, relevant to scientific and technological literacy actions, can be specified in order to fit SGC contents, as follows.

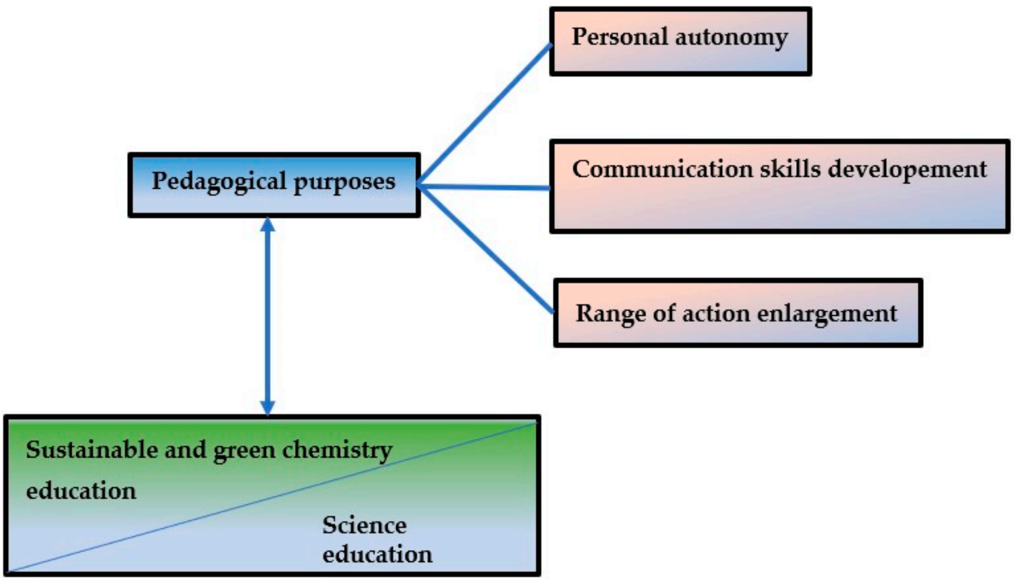

Figure 1. Pedagogical purposes of sustainable and green chemistry education.

a. Personal autonomy

This pedagogical purpose promotes individual autonomy, in order to be informed about the reasons for some practical precautions, expedients, or adaptations. For example, in the field of toxicology, it is necessary to know how to look for hazard information by examining the Safety Data Sheets, SDSs [37], or to be informed about the hidden dangers of vitamin-fortified products with associated claims of health benefits [37].

b. Development of communication skills

The ability to express 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 they reduce waste production and greenhouse effect in comparison with other materials; furthermore, microplastics could absorb pollutants in seawaters, protecting us against several diseases [38].

c. Range of action enlargement

Science is intrinsically connected to power; an individual characterized by autonomy (a) and communication skills (b) has the ability 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 associative and/or professional fields. In the first case, within safety legislation, single individuals can be involved actively as Downstream Users (DUs), communicating to the 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" (if health or environmental problems have been excluded). Schools must get involved too; there is a growing need to concretely apply sustainability practices through safety issues and legislation [39].

Operational Goals

Operational goals formulated by Fourez [35,40] provide teachers with precise indications about teaching practice according to STL criteria [27], in order to realize the educational purposes listed above. Such operational goals are reported in Figure 2 and Table 1, with reference to SGC.

Table 1. Operational goals of sustainable and green chemistry education reporting some examples.

Students Have to Be Able to . . .	Examples
. . . consult experts.	It is necessary to understand speeches coming from different experts, finding a balance between the limits of one's own knowledge and critical sensibility exercised 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.	Representing fuel cells in a simple way allows students to understand its working principles, whereas complex cell models can discourage their use in a real context
. . . use black boxes.	In daily life, you need to handle different types 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 other cases, there is the need to open a black box.
. . . use metaphors.	Metaphors can be very useful in order to approach the working principles of green technologies, such as the use of sustainable biopolymer for soil property enhancement [41].
. . . develop interdisciplinary knowledge.	A change in consciousness is needed starting from the reduction in the distance between humanities and scientific culture, which unfortunately still exists despite the numerous interdisciplinary research fields now established as ecological humanities [42].
. . . know standardized languages.	Scientific models and techniques: since SGC is very integrated within chemistry itself [43], STL would not be possible without referring to standardized languages, techniques, and models of chemistry.
. . .negotiate not only with people, but also with regulations, things, and techniques.	An example concerns cat litter choice: synthetic silica gel cat litter is harmless compared to clay litter, wrongly considered "ecological"; indeed, clay litter is commonly produced in an environmentally degrading process using strip mining, which removes the surface layer of the soil, undermining its fertility almost irreversibly [44].
. . .translate.	It means to move without effort from one 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" [45].

Table 1. *Cont.*

Students Have to Be Able to . . .	Examples
. . .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.	Historical axis can teach about past debates carried out incorrectly; a very significant example is given by the story of 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 [46].

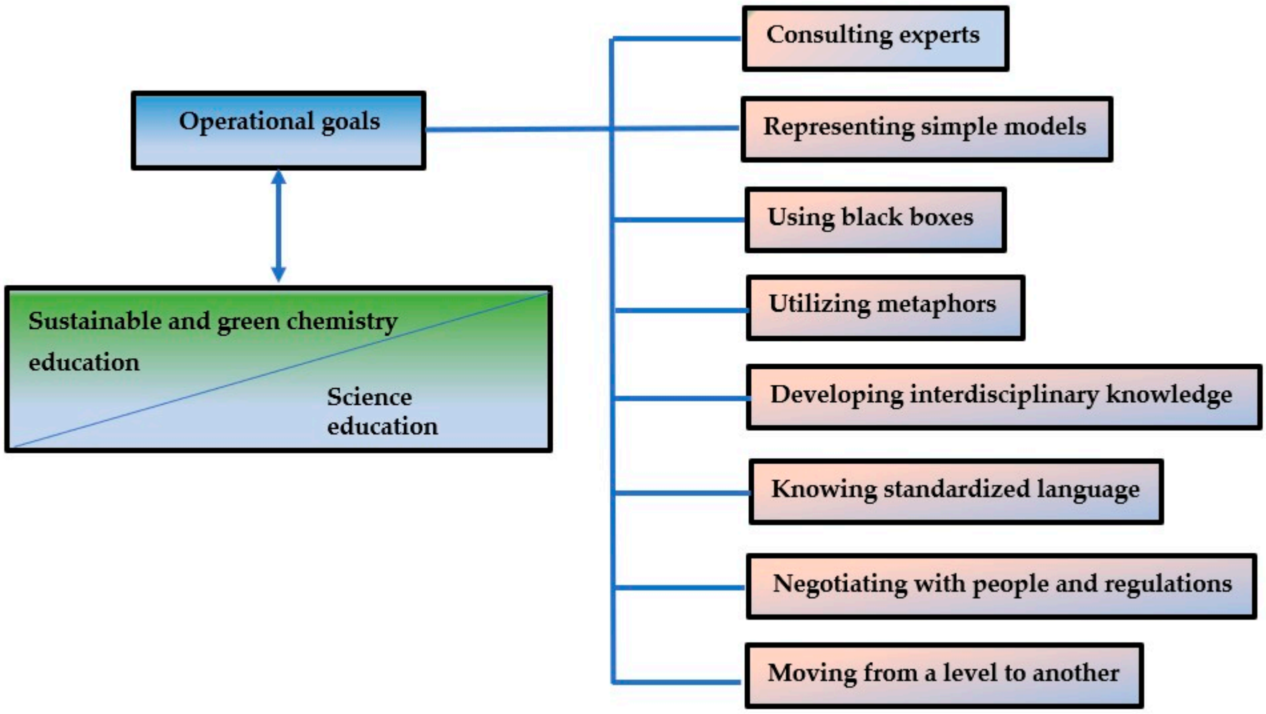

Figure 2. Operational goals of sustainable and green chemistry education.

4. From STSE to Systems Thinking in Chemistry

Widespread scientific awareness is considered an important factor to ensure the survival of democracy, according to scientists such as the winner of the Nobel Prize for chemistry, Roald Hoffmann (1937-) [47]; he wrote that the inadequate public understanding of chemistry is a barrier for the full realization of the democratic process.

STSE (Science, technology, society, and environment education) originates from the STS movement in science education from the mid-1960s to the early 1970s, emphasizing 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 [48,49]. The STSE approach has been growing also with regard to secondary chemistry education [50–54], since several countries are developing teaching programs to insert at this level of education subjects such as acid rain, global warming, greenhouse gases, nuclear wastes, fossil fuels, polymers, fuel cells, artificial sweeteners, chemical food additives, fertilizers, pesticides, air bags, pharmaceuticals, cosmetics, and so on.

Afterwards, chemical education researchers contributed by devising teaching–learning methods of chemistry in systemic terms by STICE (Systems Thinking in Chemistry Education) [55], then incorporating the molecular basis of sustainability in System Thinking [56].

As an evolution of the STICE project, IUPAC [57] launched the project "Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+)", in order to empower educators to incorporate systems thinking and sustainability into chemistry, and to enable them in introducing complex issues. Indeed, Complexity Science is undoubtedly valuable for achieving the United Nations' aims about sustainable development of our world [58].

Despite these efforts, chemistry does not enjoy a good reputation [59]. This hostility is combined with a sort of deferral to the so-called "experts" on environmental issues even by teenagers [17]. With good probability, students' perception about chemistry is conditioned by a general negative consideration, caused by pollution due to large-scale chemical production [42]. Therefore, in order to examine the peculiar situation of chemistry today, is necessary to fully understand students' disaffection toward this discipline through a historical approach, as reiterated later.

5. Dimensions of Sustainable and Green Chemistry Knowledge

As shown in Figure 3, the main aims of STL (or, on the whole, of the STS/STSE movement) concern three different dimensions: political–economic, social, and purely cultural [27]. The cultural axis splits into six scopes: historical, epistemological, esthetic, corporal, communicative, pragmatic.

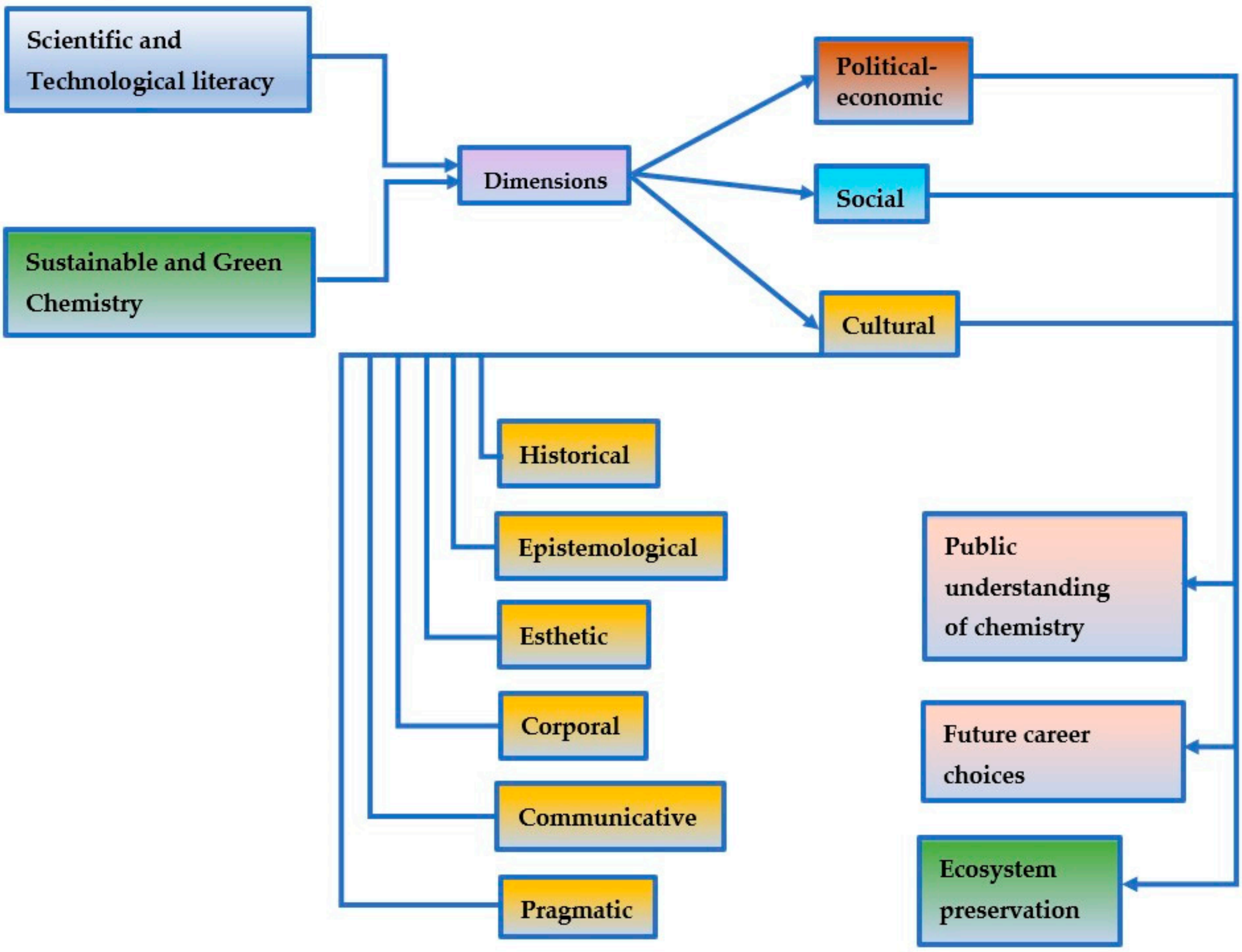

Figure 3. STL dimensions in relation to SGC, their splitting, and consequences.

Due to difficulties in learning science subjects—chemistry in particular—and the excessively slow grounding of chemistry in the educational world [26], it is appropriate to define these three dimensions of SGC for the high school level, as they are important for career choices [19] and the consequent use of chemical knowledge for ecosystem preservation [60].

5.1. Political–Economic Axis

The political–economic axis depends on the belief that a lack of scientific and technological literacy could cause a dangerous regression of developed nations (connected with the above-mentioned current of scientism [32]).

The rise of SGC has been described as a sort of revolution, in the same way as agricultural and industrial revolutions that characterized particular periods in previous centuries. SGC is very integrated within chemistry itself and cannot be treated as a separate discipline; this 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 [43]. There are several drivers for change towards SGC; specific drivers and their relative importance are certainly situational, and their influence is interconnected. Clark [61] described and analyzed several key drivers in detail, showing how they stem not only from environmental issues, but also from economic and social factors.

5.2. Social Axis

The social axis is based on the idea of democracy maintenance; for example, democratic governmental choices about the usage of food additives or pesticides suppose public debates with the participation of informed people. Hoffmann [47] highlighted the importance of correct and complete information from chemists, fearing the danger of ever greater hostility towards synthetic products in the common imagination, always and in any case harmful. One remedy proposed by Hoffmann [47] consists in a different approach from chemists, more sympathetic towards the layman, using forms of communication that induce ordinary citizens to more rational and cautious considerations. SGC education could be a royal road for a better “social reception” of chemistry, finally rehabilitated in the eyes of the general public. That is important in order to counteract chemophobia, according to which everything “chemical” is a source of danger, while everything “biological” is good and positive [59].

5.3. 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 a source of life pleasure. The cultural axis splits into other dimensions, as described below, starting from history and epistemology.

5.3.1. 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 by public opinion. It is possible to establish a precise year as a reference point for this phenomenon: the publication of “Silent Spring” [62] 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 the national, then at the international level. A general renewed environmental awareness led to the formation of the US Environmental Protection Agency (EPA). Many pesticides were banned or their usage was restricted, in particular DDT (which gained popularity after its use during World War II to prevent the spread of diseases such 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 research, studying dozens of reports and interviewing experts; her purpose was not to ban all the chemicals used in agriculture, but to understand risks for human health and the environment and to evaluate the usage of other products or biological alternatives [63].

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.

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 environmental equilibria (environmental chemistry) and their maintenance in coexistence with the production and usage of chemicals (SGC). The first important environmental chemistry publications about natural waters [64] and atmosphere [65] 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-authoring a ground-breaking book in which the "12 Principles of Green Chemistry" were outlined [66]. Thirteen years later, he wrote about the goal of the chemistry community: to design chemical products and processes that reduce or eliminate the use and generation of hazardous substances [67].

More careful studies show a bifurcation in relation to the birth and evolution of green chemistry and sustainable chemistry [10], and the many origins of green chemistry, depending on the country considered (for example, EPA researchers were driving forces in the formation of this new field in the US, whereas in the UK, the deteriorating public image of chemistry was decisive; in the Netherlands, the search for renewable resources and raw materials mostly guided the process [68]).

Although green chemistry was officially born in recent times, its premises are actually more remote. A significant example is given by the research of Giacomo Ciamician (1857–1922) in the field of photochemistry [69].

5.3.2. Epistemological Dimension

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

The role of environmental chemistry has been increasing worldwide because of the growing pressures to protect human health from exposure to hazardous chemicals [70]. The resulting chemical industry legislation may be the ideal basis for the development of green educational programs [39].

Balaban and Klein [71] 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 the features of the interdisciplinary and systemic view of chemistry (including environmental aspects) and the related use in teaching practice seems broadly positive, regardless of their differences in the background [72].

5.3.3. 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: the pursuit of practical elegance where the core principles of green chemistry are used in developing synthetic strategies [73], for example, by catalysis [74].

SGC is also applied in cosmetic sciences [75]. Furthermore, cross-disciplinary fields are realizing the communion between art and SGC, combining ethical and aesthetic values [76].

5.3.4. Corporal Dimension

The corporal dimension allows us to perceive technological tools as a particularity of human intelligent nature. Solar and lithium batteries are good examples of technologies that are part of our daily lives, as are catalytic converters of cars or environmentally friendly building materials. Another example is constituted by the photosynthetic glass [77] aimed at realizing artificial photosynthesis, considered the Holy Grail of sustainability [78].

5.3.5. Communication Dimension

Science contributes to shaping a shared view of the world. Investments visible to the general public and the dissemination of SGC practices are extremely important for future improvements. SGC has a multidimensional impact; it affects our health and environmental sustainability in many ways. Unfortunately, most people do not believe that chemical industries are concerned about the development of sustainable actions [79], whereas chemophobia is widespread [59].

5.3.6. 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 the toxicology curriculum is very significant; this allows an increased concern for chemical safety, a particular awareness of chemical hazards, and a greater readiness on how to avoid or minimize chemical exposure potential in certain situations [37,80].

6. Sustainable and Green Chemistry: Epistemological Roots and Didactic Efficacy

Historical and epistemological considerations—briefly mentioned above—provide reasons for considering the importance of philosophy and history of chemistry in chemical education [81,82]. This also applies in relation to sustainable chemistry education. Teaching chemistry in a context as broad as that of sustainability must not deprive this discipline of its intrinsic peculiarity, so history and philosophy can help educators in focusing on chemistry's unique features [83].

The importance of the historical–philosophical approach has been represented through additional dimensions of chemical knowledge—macro, submicro, and symbolic—considered by Johnstone [84]. First, Mahaffy [85] suggested a tetrahedron model (based on Johnstone' triangle) where the top represents the human element. Subsequently, Sjöström [86] proposed a subdivision of the top into three other levels: applied chemistry, socio-cultural context, and critical–philosophic approach. In this way, research fields such as environmental education become part of the chemistry teacher's training [86], in accordance with the STSE movement.

Vilches and Gil-Pérez [87], after realizing that education for sustainability remains practically absent nowadays in many high school and university chemistry curricula all over the world, analyzed main obstacles; for example, one reason is connected to the use of the content-driven approach in the majority of chemistry lessons, and to the lack of interdisciplinary-systemic treatment. According to these scholars, the deep meaning of "sustainability" has not yet been really internalized by citizens; concepts such as "competitiveness" must be analyzed from a global viewpoint, in order to understand the need to transform current competitive economic globalization into a democratic and sustainable project. Wide-ranging educational aims need to be incorporated into an appropriate educational framework, both formal and informal, including teacher training [87].

Talanquer [88] proposed the inclusion of sustainable action among the "central ideas" in chemistry, so as to fully embed sustainability at the heart of chemical epistemology. Translating renewed central ideas into curricula demands a shift in the way students are engaged with core chemistry content; this is an example of how philosophical studies can have an impact in aligning chemistry education with actual goals. Below, there are some results demonstrating the effectiveness of some approaches, from STSE to systems thinking and complex systems study.

Some Education Research Outcomes

Zoller [89] highlighted that the STSE approach must be applied to chemistry teaching in order to develop students' HOCS. According to Zoller [90], traditional methods are algorithmic, oriented to low-order cognitive skills (LOCSs), and structured in accordance with inadequate paradigms. It is necessary to shift from economic and technological growth at any cost to sustainable development; from corrective responses to preventive action; from a disciplinary to interdisciplinary perspective; from teacher-centered instruction to student-centered learning.

Several works of empirical research show the LOCS-HOCS transition with renewed education approaches. Within a pre-, post-, and post-post experimental design, high school students were divided into three groups: the experimental group (science students exposed to HOCS-promoting teaching) and two control groups (science and non-science majors traditionally taught). By using critical thinking assessment instruments, the experimental group showed a statistically significant improvement on several critical thinking skills components [52], for example, such as those described in Table 1 (ability to negotiate, debate, to be decision-makers).

Another study based on a research model where pre- and post-tests were administered to control and treatment high school student groups referred specifically to chemistry. Data obtained by the Chemistry Achievement Test (CAT) were analyzed through a particular software. As a result of the study, statistically significant increases were observed in the achievement levels of the treatment group, which received instruction using STSE relations [51]. When the CAT was matched to the Career Choice Questionnaire, the study concluded that chemistry education in relation with STSE would lead students to choosing science and technology fields for their future careers [50].

A particular quasi-experimental study examined the impact of the STS approach on chemical equilibrium understanding. Also, in this case, the STS learning approach gave better results on the students' cognitive learning outcomes [53]. Many more achievements concerning qualitative and quantitative research on the STSE approach in high school chemistry are available in the literature [54].

Collaboration between academics and motivated secondary school teachers attempts to foster wide-ranging chemistry teaching in the name of sustainability, for example, by open-ended systems maps [91,92]. It is possible to state that methods based on systems thinking have implemented instances of the STSE approach in a systemic perspective. Student-generated maps do not measure systems thinking capability directly; however, drawing the maps offers to students the opportunity to develop their systems thinking capacity within the framework of STICE [55], as demonstrated in six Australian high schools by qualitative research [92].

Such maps can be understood as "islands of interdisciplinary rationality", according to the expression coined by Fourez [35,36], who posed the question: "Where, when and how do we teach the young how to invent interdisciplinary rationality islands when faced with situations of everyday life?" System thinking expands the islands of interdisciplinary knowledge beyond everyday life to address planetary issues, highlighting global–local connections.

Systems thinking quantitative assessment presents major obstacles as compared to the STSE approach, due to the many facets of the skills to be measured. Systems thinking assessment rubrics should take into account items such as system function, system structure, and system behavior [55]. The ChEMIST (Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach) table is a useful tool, moving from less to more holistic aspects of systems thinkers to be evaluated [93]. The use of systemic diagrams and systemic assessment questions shows that traditionally taught students do not reach higher levels of systems thinking; moreover, the experimental group of female students outperformed the males when the systemic approach was used [94].

Systems thinking is essential for moving away from reductionism to a complex systems perspective. Complexity Science will bring benefits for achieving the UN 2030 Agenda [58]. More prominent inclusion of complex issues into science teaching could motivate girls. This conclusion was reached by a cross-cultural quantitative study that examined the approach of physics, chemistry, and biology teachers [95]; hard sciences (like physics and chemistry) and life sciences (like biology) reflect an epistemological difference between ordered (linear) and complex (non-linear) systems. Therefore, physics/chemistry teaching differs in a characteristic way from biology teaching; biology teachers adopt a more systems-oriented perspective. For physics and chemistry, an indirect effect of gender on motivation was found, while motivation to learn biology did not show any gender effect. The data obtained suggest that physics/chemistry teachers could find a better way if they learned from their fellow biology teachers, mostly using complex contexts and hermeneutic teaching approach [95]. That is particularly suitable in order to understand public discourse on environmental issues, trying to avoid the phenomenon of eco-depression in high school students. Conversations about the nature of science, complexity, and ethics might help teenagers learn new interpretive repertoires to address environmental challenges [96].

7. Final Considerations

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 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 the education system, obtaining STL goals in a capillary way. Environmental education and chemistry still have a conflicting relationship, as demonstrated by research about SGC in high school chemistry syllabi and instruction practice. Chemistry educators are putting a lot of effort into devising teaching–learning methods of SGC using system thinking, so as to highlight the fundamental importance of chemistry in sustainable development. Such educational practices are legitimized by numerous and increasingly important studies concerning the history and philosophy of chemistry.

After specifying the different meanings of environmental, green, and sustainable chemistry, the article hinted at the different historical developments of the latter two. The relationship between chemistry and environmental education has always been difficult. This was one of the factors that conditioned scientific careers in the chemical field, crucial for ensuring environmentally friendly development. A major contributor has come from STS movement, which has resulted in the goal of providing everyone with STL. This paper offered a short list of tools in order to identify different foundational axes of SGC (political–economic, social, cultural) within the STS/STL framework, after providing some operational goals useful for chemistry educators; all the pedagogical purposes listed require moving beyond the insularity of chemistry. Because "the environment" is not a single, isolated system, all aspects of civilization are bound together in an interconnected web (social justice, public health, economic prosperity, and so on). The STSE movement, which devoted more attention than STS to environmental issues, has had a certain relevance in secondary school chemistry education.

A particularly important step was the integration of chemistry teaching into the systems thinking approach, creating a more organic and interconnected vision of global dynamics, and preparing the ground for the study of complex systems and of the fundamental importance of sustainability studies. Several qualitative and quantitative works of research proved the effectiveness of teaching–learning methods in which chemistry is directly involved in environmental aspects. In particular, the systemic vision that preludes the study of complex systems seems to benefit girls, reducing the gender difference emerging (albeit with a certain variability) from surveys on interest and results in scientific subjects.

Chemistry educators can use their leverage to motivate younger generations. A solid preparation can provide teachers powerful tools for mastering educational challenges in GSC. For this reason, pre-service and in-service teachers' training must include:

- a solid background in epistemology within the framework of a coherent social shaping of science philosophy, showing that scientific conceptualization always stems from a context;
- specific tools to ensure the successful completion of interdisciplinary projects, integrating physical, ecological, biological, economic, ethical, and legal components;
- the opportunity to participate in debates on the goals and aims of chemistry teaching (teachers should be aware that the problem of teaching GSC is not only a technical issue, but that it also relates to ideological issues);
- some knowledge of the history of science and technology; it would be difficult for a teacher to help pupils to understand how GSC is part of a human historical process without an appropriate knowledge of its history.

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