Quim. Nova, Vol. 47, No. 9, e-20240049, 1-8, 2024 http://dx.doi.org/10.21577/0100-4042.20240049

SUSTAINABILITY, SUSTAINABLE DEVELOPMENT, SUSTAINABLE CHEMISTRY, AND GREEN CHEMISTRY: PARALLELS AND INTERCONNECTIONS

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Received: 03/11/2024; accepted: 05/13/2024; published online: 06/28/2024

The interconnectedness between sustainability, sustainable development, sustainable chemistry, and green chemistry is evident in the pursuit of innovative solutions that can balance economic, environmental, and social needs, thereby building a more sustainable future for present and future generations. Although these are topics that have been widely discussed in recent years, there are many controversies regarding the exact definition and scope of these terms. The term "Green Chemistry" was defined with the Twelve Principles of Green Chemistry, but in recent years, aspects of environmental and social costs need to be incorporated into the definition. Historically, green chemistry has tended to focus on the process, i.e., how a product is made, rather than the properties of the product. So, we generally talk about a process being green or not. This contribution aims to discuss the parallels, interconnections and differences that exist among the concepts within the realms of "Sustainability", "Sustainable Development", "Sustainable Chemistry", and "Green Chemistry". Additionally, it discusses how these topics play a crucial role in mitigating environmental impacts, conserving natural resources, generating employment, and promoting safer and more sustainable products and processes.

Keywords: sustainability; green chemistry; environment; society; economy.

INTRODUCTION

The terms "Sustainability", "Sustainable Development", "Sustainable Chemistry" and "Green Chemistry" play fundamental roles in the debate about the future of the environment, the evolution of the bioeconomy, addressing social issues, advancing scientific research, and development of new industries. Although these concepts are closely related and interconnected, they are not synonymous, as each focus on distinct areas and can lead to different emphases or conflicts in specific contexts.

The concepts of "Sustainability" and "Sustainable Development" lack singular definitions and have blurred boundaries between them. Both represent multidimensional spaces with areas of intersection, but it is essential to highlight that "Sustainable Development" is a dimension of "Sustainability", covering different aspects of society in the search for the preservation of the environment and its natural capital, while simultaneously promoting economic prosperity and equity for present and future generations. Therefore, conflicts may arise when trying to reconcile economic growth with environmental objectives or challenges related to social equality, making the balance between these aspects a practical challenge.

There are various disciplines and approaches aimed at unraveling the comprehensive complexities of sustainability. To gain a thorough understanding of management, it is necessary to conduct studies that embrace a systemic and multidisciplinary approach. This perspective should be capable of acknowledging the interconnectivity among economic, political, social, and ecological issues, taking into account temporal and spatial dimensions. It is evident that there are assessments of sustainability-related studies. However, these analyses often concentrate on conventional management theories, such as the resource-based approach, competitive strategy, or institutional theory.[1]

These same challenges also manifest in the terms "Sustainable Chemistry" and "Green Chemistry". The realms of "Sustainability" and "Sustainable Development" play a crucial role in chemical production, and "Green Chemistry" plays a complementary role, aiming to create a future that preserves and enhances the quality of life. Figure 1 details the simplified way in which these terms are related and their boundaries.

Figure 1. *Relationship between sustainability, sustainable development, green chemistry and sustainable chemistry*

While "Sustainable Chemistry" addresses chemical industrial processes focusing on reducing pollutants, profitability, and social responsibility,[2] "Green Chemistry" seeks innovations by minimizing waste and producing substances that are less toxic and harmful to the environment.[3] Conflicts may arise when traditional chemical practices and industries resist the adoption of sustainable chemical principles, or when ethical considerations such as fair trade and human rights conflict with profit-driven chemical production.

It is crucial that these terms are properly defined and disseminated, as different sectors of society may have varying priorities and interpretations, leading to conflicts in seeking solutions that address all dimensions of sustainability. Commitment and collaboration are essential to finding solutions that benefit society, the economy, and the environment.

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Associate Editor handled this article: Nyuara A. S. Mesquita

METHODS

The text addresses an important issue related to the lack of clarity and precision in the terms used in the field of sustainability, especially when it comes to social aspects. This lack of precision can lead to conceptual confusion and hinder effective communication about fundamental issues related to sustainability.

The systematic literature review undertaken for this trial represents a careful methodological approach to addressing this issue. By consulting a variety of databases, including Google, Google Scholar, Scopus and Science Direct, researchers sought to gather a wide range of academic and scientific information on sustainability and related topics. Additionally, the inclusion of information from government agencies, trusted news agencies, and widely circulated social media sources suggests a comprehensive approach to data collection.

From the data collected, it was possible to carry out a careful analysis and synthesis of information to determine more precise and updated definitions of key concepts, such as sustainability, sustainable development, sustainable chemistry and green chemistry. This condensation of information is crucial to establishing a clear understanding of the concepts in question and helping to mitigate conceptual confusion that can arise from imprecise definitions and limited scope.

The selection of works where concepts were applied with definitions closer to the original ones is also an important step, as it helps to guarantee consistency and fidelity to fundamental concepts in the field of sustainability. Although the work is not quantitative, the process of analysis and synthesis of the collected data allows a robust qualitative approach to address the issues of defining and applying sustainability concepts. It is important to emphasize the significance of identifying and understanding key terms in the realm of sustainability, highlighting the need for a systematic and meticulous approach to address conceptual ambiguities. In any field, especially one as complex and multifaceted as sustainability, having clear definitions and conceptual frameworks is essential for effective communication and problem-solving.

The text suggests that it is possible to identify common themes, discrepancies, and areas of contention surrounding these terms. By carefully analyzing and synthesizing the gathered information, researchers can establish clearer and more precise definitions for these terms, ensuring consistency and coherence in discourse and practice. Furthermore, a systematic approach enables researchers to discern nuances and complexities that might otherwise go unnoticed, thus facilitating a deeper understanding of sustainability issues. This understanding, in turn, is critical for informing policymaking, guiding business practices, and fostering public engagement and awareness.

SUSTAINABILITY

Sustainability is an abstract and ambiguous noun. It is a multifaceted concept that is often misunderstood and misused. This term encompasses a multidimensional space, as outlined in Figure 2, highlighting various ecological, environmental, social, cultural, political, and economic aspects, making this space inherently abstract.

Future-oriented, sustainability is not a one-size-fits-all concept, as it requires careful consideration of a multitude of factors, including resource conservation, responsible consumption, elimination of hunger and poverty, addressing inequalities, and equitable development. Its abstract nature can hinder the definition, measurement, and consistent and universally agreed-upon implementation, thereby exacerbating its misuse. As anything that is difficult to measure, it is difficult to manage, consequently improvement is slow. The fact is that sustainability is a critical goal for society, as it addresses the urgent need to balance human progress with the preservation of our planet for future generations. An example highlighting this is the practice of open-pit mining, which has been destroying large areas of tropical forests, leading to the release of stored carbon from trees, loss of biodiversity and air and soil pollution. Gold mining is a human activity that involves chemistry and has significantly contributed to the devastation of forests. Consequently, it has led to climate change, impacting human health, disrupting indigenous communities, and violating human rights.[4]

In Brazil, considering the economic activities involving chemistry, which plays a central role in virtually all dimensions of sustainability except in political decisions, the movement in Chemistry post-2022 was launched for the construction of an action plan aimed at guiding the practice of chemistry and its industrial actors.[5] The goal is to establish scientific foundations that impact the country's sovereignty through actions encompassing the various dimensions of sustainability. It is essential for individuals, businesses, and governments to strive for a deeper understanding of importance of chemistry to sustainability and its practical implications to promote more responsible practices and safeguard the well-being of the planet.

Figure 2. *Sustainability is a multidimensional space*

Sustainability is directly linked to atmospheric greenhouse gases emissions, such as CO_2, CH_4, N_2O, etc., which exposure the planet to high risk among others factors that directly impact the sustainability of the planet.[6] CO_2 accounts for 76% of the greenhouse effect due to being the most produced by human activities, despite its lower global warming potential (GWP) compared to CH_4 and N_2O.[7] The concentration of CO_2 in the atmosphere continues to increase, despite all the efforts of global governance through the United Nations Climate Change Conferences (COPs) and the decisions of the UN (United Nations) general assemblies.[8] In 2022, CO_2 emissions grew by 0.9%, i.e., a total of 36.8 gigatons of CO_2,[9] with a growing trend in CO_2 emissions, as between May 2022 and May 2023 there was an increase of 0.7%.[10] It is important to compare emissions in the same months, as CO_2 concentrations drop during the summer months, as plants absorb through photosynthesis what they release through respiration.

Global warming destabilizes the environment mainly through the use of fossil fuels.[11] This warming affects several climatic parameters that lead to extreme events that act against the sustainability of the planet and have negative effects on all existing fauna and flora. There are many alternatives such as biomass, which are non-fossil organic materials that occur naturally or are waste from human activities, containing intrinsic chemical energy with the potential to offset fossil fuel emissions. They are quite diverse and come from agriculture, forestry, and urban waste and are made up of a variety of different materials, including wood, crop residues, sawdust, straw, manure, waste paper, sewage and domestic waste.[12] Figure 3 summarizes the effects of global warming on the environment, including extreme weather events and actions on humanity.

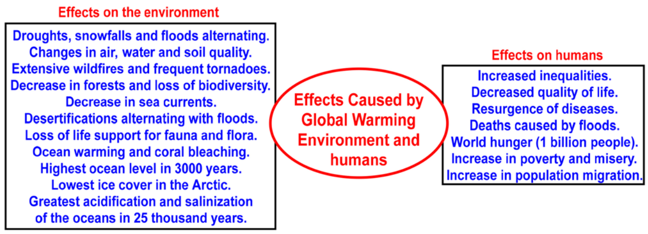


Figure 3. *The effects of global warming on the environment and humanity*

Without exception, all species of fauna and flora on the planet have their appropriate environmental niche in which their proliferation and survival reach their maximum. For thousands of years, humans have concentrated on Earth in specific areas of mild climates with average annual temperatures around 11 to 15 °C. This distribution is known as the human temperature niche and depending on population growth and global warming it is predicted that billions of people will fall outside the ideal climate conditions that have served humanity for the last 6,000 years.[13] Lenton *et al.*[14] estimated that if the world continues on the warming trajectory, it will heat up to 2.7 °C by the end of the century. This means an estimated 1 to 3 billion people will be placed under dangerously hot conditions and therefore outside the most comfortable human temperature niche. This average increase in global temperature will also lead to the extinction of millions of fauna and floral species. However, many small and large species have changed their habitat to climates different from those they lived in before due to human expansion (agricultural activities and urbanization). As a result, current mammal distributions do not accurately reflect the climatological conditions where the species lived, for example.[15] Another worrying effect of global warming is the melting of sea ice and permafrost that could finish between 2030-2050. The Arctic Ocean could have a surface area of less than 1 million km^2 of ice, with only a few fragments along the coast.[16]

Sustainability has much broader connotations and ancient, deep roots. Their concerns are distributed across multiple dimensions that were not present in the past. However, since the UN assemblies began to deal with this issue with more intensity, the issue has recently advanced rapidly in society. Among these dimensions, there was the idea that part of the problems was related to the activities of the chemical industries. The chemical and pharmaceutical industries face serious environmental problems due to the large amounts of waste generated by the classic synthetic methodologies that are still used. From this observation, the paradigms of green chemistry and sustainable chemistry aimed at protecting the environment and social well-being associated with the quality of life of men and women were created. Despite all the advances, it is necessary to emphasize that chemistry is important, but it urgently needs to improve and adapt to all dimensions of sustainability. By the year 2030, chemistry can contribute to solving our global challenges and achieving development objectives (Sustainable Development Goals, SDGs), reaching 6.6 billion euros. Trend data suggests that projected growth in the global chemical market will increase chemical releases, exposures, and adverse health and environmental impacts.[17]

The dimensions of sustainability are undermined by the policies of some countries that encourage the global market to perform towards infinite profit or infinite GDP (gross domestic product) growth on a planet with a finite supply of natural resources. Associated with these policies are the perverse ideologies and neglect of citizens that undermine the very survival of humans by annihilating the environment in which they live.[18] A planet has survived many events and that was once robust has become sick, as the priority of humans has changed to economic security, military security, and war industries that above all cause a lot of environmental damage, rupture of the social fabric, unfair treatment, misery, famine and forced migration. In this sense, any proposal that does not include poverty and hunger cannot be considered sustainable.[19]

SUSTAINABLE DEVELOPMENT

Sustainable development is the path to sustainability and is centered on various methods and strategies to achieve sustainability, such as technical or technological means, ecological and social actions, economic foundations, environmental justice, political decisions, and respect for natural capital.[20] The sustainable development objective is to make economic development compatible with the protection of the natural environment, integrating the economic aspirations of companies with the expectations of a healthy environment.[21,22]

The United Nations' 2030 Agenda for Sustainable Development was adopted in September 2015, consisting of 17 Sustainable Development Goals (SDGs) and 169 targets. The challenge lies in the implementation of the agenda to make strides in the economic, social, and environmental dimensions of sustainable development worldwide.[23]

The idea of sustainable development, in principle, are two words that do not fit together and that cause concern. To achieve sustainability, partnerships or symbiosis will be necessary between the economic, social, and environmental areas, which have long been on opposite sides. Development, as established, presupposes GDP growth and this growth places more products on the market available for consumption (or consumerism) which increases profit, which consequently increases the use of natural capital. This cycle is not sustainable and should not reproduce the economic matrix that has been in force for millennia, that is, the economy that needs constant growth at all costs. It is important to highlight that flourishing economies and environmental deterioration cannot coexist, as achieving environmental sustainability also entails risks that could have an impact on business operations and prospects in a fiercely competitive market. Therewith, sustainable development was misunderstood and, at times, deliberately misused, as it should consider three indicators: (*i*) viable economy (energy consumption *per* inhabitant, renewable energy consumption, GDP expenditure on environmental protection, responsible use of natural resources); (*ii*) social responsibility (infant mortality rate, life expectancy at birth, GDP expenditure on health, unemployment rate, number of employed women, hunger, poverty, etc.)[24,25] and (*iii*) protected environment (control of toxic gaseous substances, ozone layer, water consumption, natural capital, water, air and soil pollution, deforestation, overexploitation of natural resources, etc.). This theory was named in 1994 by John Elkington[26,27] such as "Triple Bottom Line (TBL or 3BL)" or the "3 'Ps' rule" (profit, people, planet),[28,29] which introduced sustainability principles into business organizations.[30] According to its definition, industries must evaluate the three segments when planning their strategies, as all three are characterized by the same importance, not only accounting for financial return.[31] However, previously, the concept of environmentally sustainable economic[32] development already existed, which considered that the global objectives of environmental conservation and economic development are not conflicting.

To be sustainable, the central policy must reconcile development that follows the "Triple Bottom Line" theory. In simpler terms, the TBL agenda focuses on companies not just on the economic value they add, but also on the environmental and social value they add.

The actions recommended in the TBL must meet the needs of the present without compromising the ability of future generations to meet their own needs. This statement was already contained in the 1987 Brundtland Commission report – "Our Common Future - A Global Agenda for Change".[33] This publication introduced the term "Sustainable Development" into the political, economic and business mainstream, emphasizing that if these decisions are not ecologically rational, we will be unable to maintain living standards for all species on the planet. In this same sense, ESG (Environmental, Social, and Corporate Governance) and the Corporate Sustainability Index (ISE B3) were created.[34-36] The objective of ISE B3 is to be an indicator of the average performance of companies selected for their commitment to corporate sustainability. This index is seen as a recognition of the company for its sustainability and social responsibility practices. As an example, we can mention companies in the B3 food subsector that adhere to SDG 2 (Zero Hunger and Sustainable Agriculture).[37] Darolt *et al.*[38] analyzed the sustainability reports of companies belonging to ISE/B3 in the year 2023 and found only 4 organizations with actions that promote the sustainable agriculture and combating hunger. ESG represents the three key areas of corporate responsibility and sustainability: environmental, social and corporate governance. These three factors are widely considered important for evaluating the performance and responsibility of companies in relation to issues of sustainability, ethics, and social responsibility. They are very similar to what was established by John Elkington in the "Triple Bottom Line" theory.

In pursuit of Sustainable Development Goals, addressing the impact of artificial intelligence on sustainable development is of great relevance. Studies[39,40] have shown that Google's AlphaGo Zero generated 96 tons of CO_2 over 40 days of research training which amounts to 1000 h of air travel or a carbon footprint of 23 American homes. Other studies[41] illustrated that the process of training a single, deep learning, natural language processing (NLP) model (GPU) can lead to approx. 600,000 lb of carbon dioxide emissions. When compared this to familiar consumption, you are looking at roughly the same amount of carbon dioxide emissions produced by five cars over the lifetime of the cars. For these reasons, we must keep in mind the difference between artificial intelligence (AI) for sustainability *versus* the sustainability of AI. AI for sustainability holds great promise but is lacking in one crucial aspect; it fails to account for the environmental impact from the development of AI. And sustainability of AI is focused on sustainable data sources, power supplies, and infrastructures as a way of measuring and reducing the carbon footprint from training and/or tuning an algorithm. It is necessary to unite these two aspects to ensure the sustainability of AI for the environment.[42]

SUSTAINABLE CHEMISTRY

In 1998, the Organization for Economic Co-operation and Development (OECD) organized a Workshop on "Sustainable Chemistry". At this event, a definition for this term was established: "within the broad framework of Sustainable Development, we should strive to maximize resource efficiency through activities such as energy and non-renewable resource conservation, risk minimization, pollution prevention, minimization of waste at all stages of a product life-cycle, and the development of products that are durable and can be re-used and recycled. Sustainable Chemistry strives to accomplish these ends through the design, manufacture and use of efficient and effective, more environmentally benign chemical products and processes".[43]

Considering this definition, sustainable chemistry is more comprehensive and permeable than green chemistry, as it addresses several other aspects of environmental policies, sustainable and socially fair practices, adoption of public sustainability policies and sustainable economic development. However, it is worth remembering that the concepts and definitions of sustainable and green chemistry seek to achieve economic advances in accordance with the objectives of protecting the environment and the health of humanity. The actions induced by green chemistry focus mainly on minimizing the environmental impacts caused by chemical reactions and their byproducts. Sustainable chemistry covers not only waste reduction, mitigation of environmental pollution, minimization of toxic chemicals (which are the main focuses of green chemistry), that is, it includes all the concepts and principles of green chemistry.[44] The adjective sustainable, if properly used, can be applied to many scientific and everyday activities, such as sustainable surfactant, among many others.[45] In reality, it includes a broader system than just the specific reaction, but considers issues such as efficiency in the use of resources, social justice, mitigation of environmental damage caused by chemicals, economic development, equity in the distribution of benefits, life cycle when evaluating chemicals and processes, human health impacts, and production impacts. It is also concerned with the chains of use, transport, disposal and recycling. This takes into account impacts at all stages, from cradle to grave, and not just initial production, that is, it seeks to integrate the public and private sectors, as well as civil society, in the search for sustainable solutions. Green chemistry is a fundamental part of sustainable chemistry that incorporates a broader perspective and considers the challenges and opportunities that involve chemistry and its relationship with the environment, society and the economy in a more comprehensive and holistic way.

In August 2023, through a report from the National Council on Science and Technology of the US Presidency,[46] a negotiated and consensual definition of sustainable chemistry was proposed, as well as a working structure and attributes that characterize it for a robust assessment with new, updated criteria. In essence, this means a scientific endeavor that is a work in progress. This report made a current interpretation: "sustainable chemistry is the chemistry that produces compounds or materials from building blocks, reagents, and catalysts that are readily-available and renewable, operates at optimal efficiency, and employs renewable energy sources; this includes the intentional design, manufacture, use, and end-of-life management of chemicals, materials, and products across their lifecycle that do not adversely impact human health and the environment while promoting circularity, meeting societal needs, contributing to economic resilience, and aspiring to perpetually use elements, compounds, and materials without depletion of resources or accumulation of waste". The way it was defined makes it evident that the definition resembles green chemistry,[47] which was to be expected since sustainable chemistry encompasses a broader set, including the entire green chemistry approach. Although this definition does not directly mention the mitigation of environmental pollution, it highlights the importance of limiting the life cycle of products, promoting the circularity of these products, dealing with the accumulation of solid waste, ensuring economic resilience, considering health impacts and meet social needs. Therefore, this definition not only incorporates the principles of green chemistry but also expands its scope to other areas relevant to society.

GREEN CHEMISTRY

Most of the contamination problems of soil, air, rivers, lakes, and oceans that led to many environmental and health problems were caused by chemical waste that was dumped into the environment between the 1940s and 1980s, such as

DDT (dichlorodiphenyltrichloroethane) (Figure 4).[48] With approximately 1.5 teragrams (1.5×10^{12} g) produced worldwide,[49] even resulting in a Nobel Prize for Swiss chemist Paul Hermann Müller for the discovery of its insecticidal properties, the DDT case is emblematic because it was the result of disregard for an insecticide that was freely sold and applied to people and agriculture without measuring its toxicological consequences. From this specific case among others, it is hypothesized that with the scientific knowledge we had during this period we could have done much more in regulatory terms, inspection and engineering against the production and dumping of chemical products into the air, water bodies and soil.

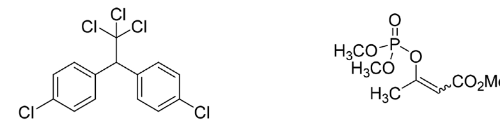
The first voice to speak out against DDT was Rachel Carson who wrote the book "*Silent Spring*"[50] after receiving a letter from a woman named Olga Owens Huckins telling her that DDT was killing birds. Colossal denialist forces driven by financial interests tried to disqualify the book and the author, but even so, the uses and production of DDT have been banned in the USA after all the damage it caused to the environment, leaving only those that are already disseminated in plants, sediments, and soil, and which will take years to degrade.[51] The ban was not automatic in all countries. In Brazil, sixty years after the closure of the DDT factory and other organochlorine pesticides, several areas of land and facilities remain contaminated. The blood tests from 95% of 1,400 inhabitants around the factory indicated the presence of high residues of DDT.[52] The case of pesticides is quite significant, as it exemplifies how a chemical product that was approved without exhaustive toxicological tests and with degradation problems was considered safe.

The DDT case is classic and has been partially resolved, but currently environmental contamination by chemicals has expanded to the areas of pesticides and heavy metals. Many of the pesticides that are released into the external environment for agriculture, forestry, fishing and the food industry have not had complete toxicological studies. In this case, new information may emerge about these commercial products and substances that were previously considered sustainable may no longer be safe for humans.[53] Scientist Larissa M. Bombardi[54] (FFLCH-USP) wrote an atlas on the safety of pesticides, the devastation of environmental fauna and the effects they cause on workers despite chronic exposure to pesticides in general are difficult to account for. The atlas emphasizes that 30% of the active ingredients used in Brazil are banned in the European Union, and two of these are among the ten best-selling in Brazil.

In the epigraph of the book of Rachel Carson,[50] there is a quote from the German philosopher and doctor Albert Schweitzer that still reflects what exists today: "man has lost the ability to predict and prevent. He will end up destroying the Earth – from which he and other living creatures derive their food. Poor bees, poor birds, poor man." Nowadays the intensity of use of toxic agrochemicals has increased and continues to decimate the population of insects and birds in several European countries.[55] In 1962 it was already evident that the use of toxic agrochemicals could affect wildlife directly and indirectly by applying pesticides through the consumption of food and water that could affect important developmental phases of their biological cycle.

First, it was insects and now it is birds. New studies claim that intensive agriculture and the use of toxic agrochemicals are decimating the bird population in several European countries.[50] Recently, pesticides killed hyacinth macaws (*Anodorhynchus hyacinthinus*) in the Pantanal (Brazil), which demonstrates disrespect for biodiversity. High levels of Menvifos (158.44 ppb) were found, which has the trade name Phosdrin (Figure 4) and can also cause damage to human health.[56]

It is important to highlight that several of these toxic products dumped into the environment have been transformed into global



Dichlorodiphenyltrichloroethane (DDT) Phosdrin

Figure 4. *Dichlorodiphenyltrichloroethane (DDT) and phosdrin chemical structures*

disasters, such as greenhouse gases, organofluorides that destroy the ozone layer, ocean acidification, coral bleaching caused by sunscreens and micro and nanoplastics, among others.

The examples highlighted above, and many other very serious ones, damaged the image of Chemistry (and still continue), which has historically been associated with industrial activities that kill and dump millions of tons of chemicals into the air, rivers, soils, lakes, oceans, food, cosmetics, etc. Some water bodies became so polluted that they even caused the death of many people, such as the Cuyahoga River in Cleveland, USA, which became so polluted with chemicals that it started at least 9 fires and in 1969 the river caught fire and burned for about twenty minutes damaging two railways.[57] This river still has problems, but not the same ones that were previously caused by chemical industries.

The bad stigma of Chemical Science still persists from the beginning of the 20th century to the present day, as many chemical and pharmochemical industries continue to act in the same way. Its effects continue to persist in the environment, emphasizing the need to reduce risks in products and processes. The environmental consequences of this legacy emphasize the urgency of planning a sustainable future and mitigating risks inherent to chemical products and processes.

It was in this chaotic scenario, caused by the uncontrolled pollution of chemical products in the environment, that the foundations of the green chemistry proposals launched by the US Environmental Protection Agency (EPA) emerged in 1990. This proposal laid the foundations for a productive collaboration between government, industry and academia. In this way, the idea of green chemistry was being propagated in academic and industrial circles, driven by the approval of the Pollution Prevention Act of 1990 (PPA) in the USA, which aimed to reduce pollution by reducing the source before it was created, which marked a shifting regulatory policy from pollution control to pollution prevention as the most effective strategy for these environmental issues.[58] The general principles of the PPA were established based on the premises: (*i*) reduce the amount of any hazardous substance, pollutant or contaminant that enters any waste stream or is otherwise released into the environment before recycling, treatment or disposal and (*ii*) reduce risks to public health and the environment associated with the release of substances, pollutants or contaminants.[59]

The expanded concepts of green chemistry were also formulated for the first time in the late 1990s and also with the objectives of reducing hazards at all stages of the life cycle, with a considerable hazard being the ability of a product to cause adverse effects to humans or the environment.[60] The 12 principles of green chemistry were published by Anastas and Warner,[61] in 1998, in a book. This book is considered a fundamental text in the field of green chemistry and discusses the importance of sustainable design in chemical processes, emphasizing that the design of chemical products and processes must reduce or eliminate the use and generation of hazardous substances. The 12 principles highlighted that the basis was sustainability, waste reduction and the development of environmentally friendly chemical processes. Since then, its principles have guided research and innovation in the field of chemistry, aiming to create more sustainable practices that are less harmful to the environment and human health. The main objective of the 12 principles was to develop chemical processes and products in a way that minimizes or eliminates the use of toxic substances, reduces the consumption of finite natural resources, minimizes adverse environmental impacts, eliminates or minimizes the use of toxic chemical substances, dangerous or harmful substances in production processes and chemicals, making them safer for humans and the environment.[62,63]

Based on these principles[64-66] research was directed towards the design of laboratory-scale products and processes that were less harmful to the environment, maintaining or improving product performance. Likewise, there was a significant increase in the production of books and the creation of scientific journals on green chemistry, which also included an insertion in education through courses, conferences and a focus on innovation[67,68] that reports about the threats posed by today's unsustainable lifestyles across much of global society.[69] Green chemistry is scientifically comprehensive, but it is inserted within the larger context of sustainable chemistry, which is more comprehensive with regard to the dimensions of sustainability from both an economic, social and environmental point of view.

Green chemistry has had wide prominence in academic and industrial circles. Its concepts began to be disseminated more quickly in academia, government, and industrial sectors in countries,[70] but without considering all the current dimensions that govern sustainability. It recommends that chemical processes that are harmful to the environment should be replaced by less aggressive and sustainable alternative processes. Although green chemistry proves to be beneficial for the environment and human health, it does not aim to mitigate the damage that has already been caused to the environment, rather than carrying out the corresponding remediation which is significantly more expensive, but reducing or eliminating future damage. Although it offers numerous benefits for the environment and human health, it is not free from future challenges and problems such as transition from bench scale to pre-pilot scale. Therefore, areas of uncertainty persist on the green horizon. Green chemistry focuses on innovative and efficient processes that are both environmentally friendly and economically viable. This is one of the biggest challenges of green chemistry, that is, to stand between a sustainable economy and quality of life.[71] The most important thing is that green chemistry has researchers interested in preventing the effect of chemical reactions and their byproducts on the environment.

To elevate the 12 principles of green chemistry to the level closest to green engineering, in 2001, Neil Winterton[72] extended 12 additional principles to the initial concepts of green chemistry at a qualitative level, aiming to add chemical experimentation in a more quantitative way. There were already some concerns that green chemistry would not cover all aspects of sustainability.[73] The 12 original principles of green chemistry associated with 12 additional principles are outlined in Figure 5. Of these additional principles, issues related to the cost of separation, elimination of reaction byproducts, heat and mass transfer, and stirring rates stand out, gas dispersion and solid-liquid contact. The cost of separating or eliminating byproducts can determine the economic viability of a process or product. By-products in small quantities are more complex to remove, as a chemical process is rarely highly specific. Another concern is the thermodynamics of the process, which may be low and safe on a small scale, but creates serious difficulties on a pilot scale.

The 12 original principles	The 12 additional principles
1. Prevention waste than to treat.	1. Identify and quantify by products.
2. Atom economy.	2. Report conversions, selectivities, and productivities.
3. Less hazardous chemical synthesis.	3. Establish full mass balance for process.
4. Designing safer chemicals.	4. Measure catalyst and solvent losses.
5. Safer solvents and auxiliaries.	5. Investigate basic thermochemistry.
6. Design for energy efficiency for chemical processes.	6. Anticipate heat and mass transfer limitations.
7. Use of renewable feedstocks.	7. Consult a chemical or process engineer.
8. Reduce derivatives.	8. Consider effect of overall process on choice of chemistry.
9. Catalysis are superior to stoichiometric reagents.	9. Help develop and apply sustainability measures.
10. Design for degradation	10. Quantify and minimize use of utilities.
11. Real-time analysis for pollution prevention.	11. Recognize where safety and waste minimization are incompatible.
12. Inherently safer chemistry for accident prevention.	12. Monitor, report, and minimize laboratory waste emitted.

Figure 5. *The original and additional principles of green chemistry*[57,65]

The issue of biodegradability and toxicity of products should be central points of chemistry and chemical engineering projects in the development of a new product.[74] Those materials resistant to biodegradation and degradation cannot be absorbed by microorganisms, remaining in the environment as contaminants.[75] They cause toxic and harmful effects on fauna and flora, some of these effects are not yet known or predictable at the beginning of development. Bioaccumulative and persistent products are of greatest concern, as they tend to accumulate in the tissues of fish, animals, plants and become more concentrated as they progress through the food chain. For example, plastic (general term) is a public health issue. It is today the second biggest environmental threat to the planet, including its contribution to global climate events.[76] They are present in water and in the food, we consume and accumulate in different parts of the human body. Its effect on the economy will be devastating if there are no advances in materials.

Economic viability is a concern for implementing green chemistry processes and products. They can be more expensive than traditional methods, discouraging chemical industries from investing in the adoption of these new technologies. However, achieving global consistency in green chemistry standards can be challenging, and if there are no regulatory requirements for new green and sustainable chemicals and processes it can be a significant challenge. In some cases, it is a challenge to find green alternatives to hazardous or toxic chemicals that have comparable performance. For example, replacing a toxic substance with a less toxic one may result in greater energy consumption or other environmental compromises. Expanding processes and maintaining their ecological characteristics can be more complex. The adoption of green chemistry practices varies around the world due to differences in regulations, shortages of raw materials, market requirements, education[77] and, economic conditions. The challenges of green chemistry with more sustainable and environmentally friendly processes and chemicals remain the most critical areas for decreasing the environmental impact of the chemical industry.

CONCLUSIONS

This manuscript emphasizes crucial points to help the reader distinguish common aspects among the terms "Sustainability", "Sustainable Development", "Sustainable Chemistry", and "Green Chemistry". These pillars must correlate social, environmental, and economic aspects. These terms often generate controversy due to overlapping definitions and areas of activity. The central ideas of these concepts involve the pressing need to reduce the human impact on the planet, requiring a reconfiguration of processes to produce materials that can circulate in the economy, minimizing waste, and maximizing reuse and recycling. Chemistry's ability to create solutions is crucial in addressing current emergencies, and efficiency in translating this chemical potential into practical and necessary solutions becomes essential.

"Sustainability" and "Sustainable Development" are expansive concepts that go beyond the realm of chemistry, encompassing economic, social, and environmental dimensions. Both provide a conceptual framework guiding actions toward a balanced and healthy future, where resources are used consciously and responsibly to meet present needs without compromising future generations.

"Sustainable Chemistry" and "Green Chemistry" are important and specific branches of these broader concepts. They focus on applying the principles of green chemistry within the field of chemistry, aiming to reduce environmental impact and develop processes and chemical products that are less harmful to nature and human health.

Understanding the interconnection between these concepts is fundamental to achieving the Sustainable Development Goals (SDGs), promoting environmental education,[78,79] interdisciplinary collaboration and professional training, in addition to reconfiguring industrial processes and social behavior.

ACKNOWLEDGMENT

We would like to thank the scholarships granted by FAPERJ CNE E-26/202.800/2017, CNE E-26/200.911/2021, CNPq grant 1A 301873/2019-4 and the FAPERJ projects under number E-26/010.101106/2018, Pensa Rio E-26/010/00168/2015, SEI-260003/001178/2020 (Temático).

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