Green Chemistry and Science Education

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Green Chemistry

The place where non-living and living elements interact in a balance that must be preserved is defined as the environment (Buckingham & Turner, 2008). Human beings, one of the living elements of the environment, have been affected and influenced by their environment. In the early times, the impact of this interaction on the environment was not destructive. However, especially during and after the industrial revolution, humans have caused destructive effects on the environment (Keleş & Hamamcı, 2002).

The industrial revolution has led to a growth in factories and transportation networks worldwide, which have improved people's lives in certain ways but had detrimental consequences on the environment. Growing industrialization processes have coincided with scientific and technological advancements, and the devastation brought about by negligent procedures has resulted in hazardous waste generation and environmental pollution issues (Liu et al., 2018; Ukaogo et al., 2020).

The chemical industry is one of the sectors that can cause environmental pollution and generate harmful waste materials. The existence of chemistry as a science dates back to 3000 BC. The science of chemistry has a very wide scope, from the production of medicines to the detergents we use for cleaning. However, when these processes are not organized in an environmentally friendly way, it has led to the production of harmful waste materials and pollution. There are various examples of this situation around the world. For example, in 1969, pollution in the Cuyahoga River in Ohio caused a fire. This situation necessitated legal regulations to clean up the river water (Anastas & Maertens, 2018; EPA, 2020). (Figure 1).

Figure 1. Cuyahoga River

As legal sanctions are seen to be insufficient, solutions have been sought worldwide. One of these solutions is the concept of green chemistry. When the dates showed 1991, the US Environmental Protection Agency (EPA) officially commenced the "Green Chemistry Program" as an alternative environmental program. Approximately 7 years later in 1998, John Warner and Paul Anastas explained the 12 basic principles of green chemistry and presented this understanding of green chemistry to the literature as a more comprehensive field (Anastas & Warner, 1998).

Green Chemistry as a Concept

When we look at the history of green chemistry as a concept, it is seen that it is not a very old one. The concept of green chemistry emerged in the 1990s from the idea of preventing pollution on site instead of cleaning up industrial pollution afterwards. In this respect, it can be said that it emerged as an alternative to the traditional pollute-clean approach. The essential point of green chemistry is the utilization of chemistry to prevent pollution. In a more comprehensive definition, green chemistry is the use and production of harmless chemical products and processes that do not harm the environment and do not cause pollution. In short, green chemistry is an understanding that establishes a link between the execution of chemical processes that do not harm human health and the environment, the production of products and environmental health (Hjeresen, 2000).

When the history of green chemistry as a concept is examined, it can be said that the first movement in the emergence of the understanding of green chemistry was the book titled "Silent Spring" penned in 1962 by Rachel Carson. One of the points emphasized by Carson in Silent Spring, which is a scientific book, is the destructive damage caused by some types of chemicals used on the environment and the consequences of this destruction. The warnings in the book attracted global attention. This book, which emphasized the seriousness of the destruction of the environment, is considered as the starting point of the main environmental movement (Sheldon, 2008).

In 1970, founded by President Richard Nixon, the establishment of the U.S. Environmental Protection Agency (EPA), an organization dedicated to improving the environment and human health, is an initiative towards green chemistry. One of the important decisions of the EPA was to ban the use of harmful chemical pesticides and DDT (Wilson & Schwarzman, 2009). Until the 1980s, environmentalist behaviors carried out by the EPA and the chemical industry were carried out on the basis of cleaning up environmental pollution. However, the global increase in concerns about environmental problems and pollution and the efforts to raise awareness and consciousness about the environment all over the world have led to a change in some understandings in chemistry science as in all fields. This change has focused on the prevention rather than the cleaning of pollution caused by chemicals that have negative effects on the environment and humans. Throughout the 1980s, meetings were organized by the Organization for Economic Co-operation and Development (OECD) to address environmental concerns. In these meetings, environmental targets were set and recommendations were made to prevent pollution. To achieve these goals, the Office of Pollution Prevention and Toxics (OPPT) was established by the U.S. Environmental Protection Agency (EPA) in 1988. This office was established to develop harmful chemicals used in industry in such a way that would be harmless to the environment and human health or to produce alternative harmless chemicals (Murphy, 2020).

The 1990s were years of significant developments in the appreciation of green chemistry as an official scientific field. The 1990 "Pollution Prevention Act" is one of the most substantial indicators of the acceptance of green chemistry (Linhorst, 2010). The conceptual definition of green chemistry was made in 1991. Anastas (1991) defined green chemistry as "designing chemical processes and products to decrease the use of hazardous substances and prevent waste" (Anastas & Williamson, 1996; Horvath & Anastas, 2007).

At the beginning of the 1990s, the European Community's Chemistry Council drew attention to the importance of green chemistry by publishing many articles on the theme of "Chemistry for a Clean World." The first scientific meeting on this subject, a symposium on "Benign by Design: Alternative Synthetic Design for Pollution Prevention," was held in Chicago in 1994. The symposium was sponsored by the Division of Environmental Chemistry of the American Chemical Society (A. O'Connell, 1995).

Another development in the 1990s was the EPA Office of Pollution Prevention and Toxins staff, who coined the term green chemistry, laying the foundations for collaboration between management, industry systems, and science. Chemists P. Anastas and J. C. Warner outlined twelve basic principles of processes for developing chemicals that do not harm human and environmental health. P. Anastas also directed the EPA Green Chemistry Program, which focused on research and education. During this time, Anastas, together with EPA staff, worked with policymakers to recognize and promote green chemistry innovations (Krasnodębski, 2022; Maxim, 2023).

In 1995, the EPA got support from politicians to establish the Presidential Green Chemistry Challenge Awards (GCCAs) program to promote, support, and encourage useful new chemical technologies that prevent pollution harmful to human and environmental health (Anastas & Kirchhoff, 2002). In 1997, the University of Massachusetts established a PhD program in green chemistry. The program in Boston was the first green chemistry PhD program. In the same year, Dr. Joe Breen, an EPA employee, and researcher Dr. Dennis Hjeresen co-founded the Green Chemistry Institute (GCI). When the Green Chemistry Institute (GCI), a non-profit organization that shapes the concept and practices of green chemistry with the highest impact at the global level, was launched, Joe Breen was its director. Another important development in the understanding of green chemistry took place in 1998. In 1998, the book "Green Chemistry: Theory and Practice," written by Paul Anastas and John C. Warner, continued to guide the green chemistry movement by summarizing 12 principles of green chemistry (Clark & Minhas, 2003; Linthorst, 2010; Sheldon, 2018).

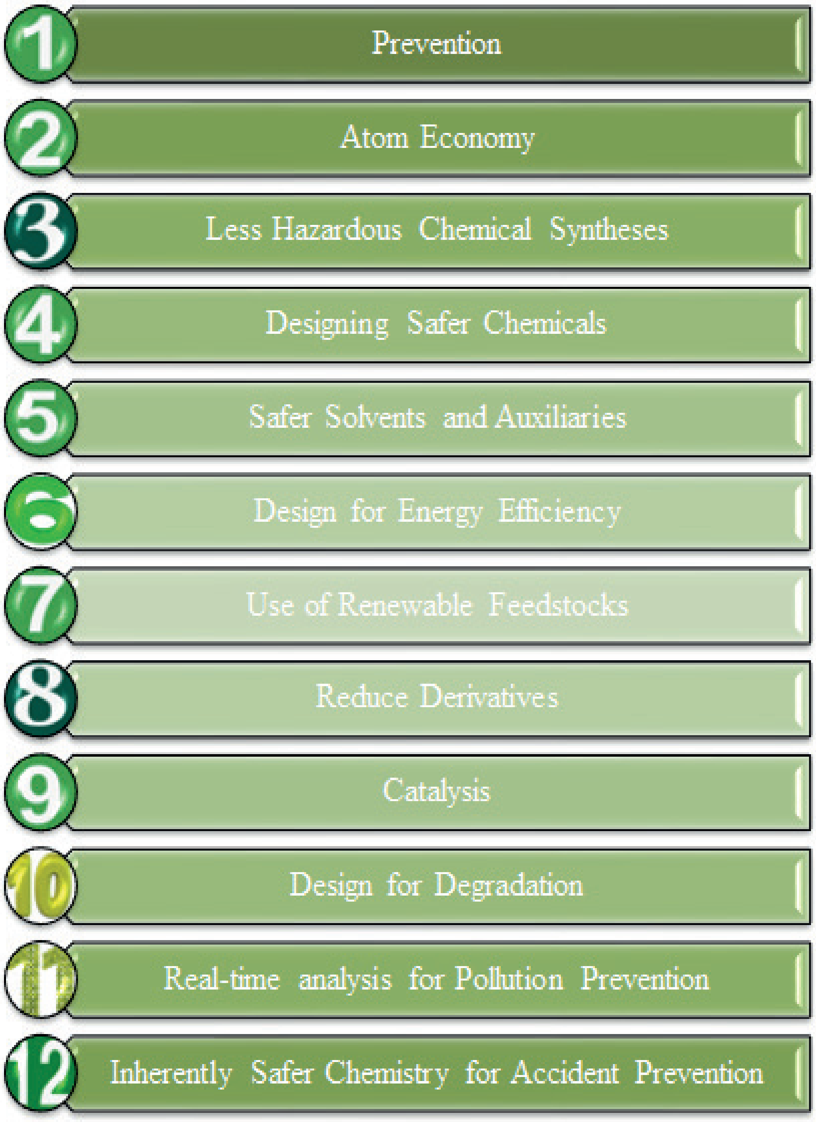
In the 2000s, it is seen that researchers around the world have adopted the principles and goals of green chemistry. In 2001 and 2005, Nobel Prizes were awarded to studies in the field of green chemistry, which is one of the biggest indicators that the green chemistry movement has attracted global attention and adoption (Dicks & Batey, 2013; Keinan, 2021).

Despite all these developments, it would not be correct to say that the effects of green chemistry are highly visible in the entire chemical industry today. Today, the raw materials used to make chemicals are obtained from fossil resources at a high rate. It seems possible to change this situation with the recognition of the field of green chemistry all over the world and the integration of its applications into all systems, especially education systems (Gerçek, 2012).

Principles of Green Chemistry

Green chemistry is a field that aims to eliminate unsafe, unhealthy conditions and pollution by reducing the production or use of products that have the potential to harm human and environmental health in the synthesis, design, production, and use of chemicals in different areas. A number of principles are applied in this process. These principles are considered as an indicator of the progress made in the field of green chemistry and as principles that guide future studies (Anastas & Warner, 2000). The outlines of these 12 basic principles, known as the basic principles of green chemistry, were established in 1998 by P. Anastas and J. C. Warner. These 12 principles are a guide to be applied at all stages, starting from the raw materials used in the chemical industry to the efficiency of the process, the safe execution of the processes, the toxicity and biodegradability of the products, and the reagents used in the process (Anastas & Eghbali, 2010). These 12 principles are listed in Figure 2 (Abdussalam-Mohammed et al., 2020).

Figure 2 : *The Twelve Principles of Green Chemistry*



The first of the 12 fundamental principles of green chemistry is the principle of prevention. The prevention principle aims to prevent pollution at the source instead of polluting first and then cleaning up the pollution. This principle is based on the understanding of not creating waste at all instead of cleaning it up after it is created (Tang et al., 2005).

The second principle is “atom economy”. Barry Trost defines the ideal reaction as containing all atoms of the reagents. Atom economy also aims to avoid waste by ensuring efficient use of the raw materials used in the process and the formation of fewer by-products (Trost, 1995). The principle of atomic economy is based on the understanding of designing synthetic methods that maximize the level of integration of all materials used in chemical processes into the end product (Dicks & Hent, 2015).

The third principle of green chemistry is the tenet of “less hazardous chemical synthesis.” This principle is based on the understanding that in all possible fields, methods should be developed to produce and use substances that do not harm the environment and therefore human health (Hjeresen et al., 2002). One of the best examples of this principle is the production of cumene (Anastas et al., 2000).

The fourth principle is the "design of safer chemicals." According to this principle, chemical products should be manufactured with high functionality to contain the least amount of toxic substances. The concept of safe chemicals is to minimize the toxicity and potential for harm without reducing the functionality of the chemical (Morales et al., 2020).

The fifth principle is "safer solvents and auxiliaries". This is based on the principle that auxiliaries used during a reaction should be used harmlessly and in small amounts. Auxiliaries used in chemical processes can sometimes have the potential to seriously harm human and environmental health, so it is better to use them sparingly and safely (Beach et al., 2009; Kerton & Marriot, 2013).

The principle six is "design for energy efficiency". According to this principle, energy needs should be evaluated and minimized by considering economic and environmental factors. In the context of this principle, if chemical transformations are designed to require less energy, the negative effects of this energy need on the environment will be reduced (Horvath & Anastas, 2007).

The seventh principle of the twelve fundamental principles concerns the "use of renewable feedstocks." According to this principle, feedstocks used in chemical processes should be renewable. In the context of this principle, feedstocks should be renewable, not consumable. Thus, sustainable and environmentally friendly systems that do not create negative pressure on the environment can be created (Clark et al., 2006; Verma et al., 2024).

The eighth principle is to "reduce derivatives." According to this principle, by-products, i.e., derivatives, used in chemical processes should be reduced as much as possible. Derivatives in chemical processes can lead to waste generation or the use of additional markers. Reducing derivatives will be a step that positively affects the atomic economy (Erökten, 2006; Kottappara & Palantavida, 2020).

The ninth principle of green chemistry is "catalysis". According to this article, the use of catalysts in chemical processes reduces waste production. Catalysts that can be used many times also positively affect the reaction efficiency (Söğüt & Celebi, 2020).

The tenth principle is an item on the end-of-function transformation of chemical products: "Design for Degradation." According to this principle, chemical products should not degrade into harmful products that have a negative impact on the environment. Chemical products can persist in the environment for many years by showing resistance in their own structure at the end of the process. The accumulation of these chemicals can have toxic effects for some species. This is undesirable for green chemistry. In the understanding of green chemistry, chemical products should turn into harmless decomposition products at the end of the process (Demir, 2017).

The eleventh principle is a clause on "real-time analysis for pollution prevention." Waste or pollution generated by chemical processes is undesirable for green chemistry. According to this principle, in order to prevent waste or pollution at the end of chemical processes, methods should be developed to monitor and control the entire process (Hjeresen et al., 2000; Yayayuruk & Yayayuruk, 2019).

The final principle of green chemistry, the twelfth principle, is the idea of "inherently safe chemistry for accident prevention." According to this principle, substances used in chemical processes should be selected by taking into account their accident-causing properties. In the understanding of green chemistry, the substances utilized in chemical processes should be selected in such a way that minimizes the potential to cause accidents. In this context, inherently safe chemicals should be produced and used (Mulholland et al., 2000).

Reflections of Green Chemistry Practices on Science Education

It is a necessity to integrate the understanding of green chemistry, which aims to make chemical processes more sustainable by reducing chemical use and waste generation, which are risk factors, into education and training environments. Today, many different industries and fields are operated with chemistry knowledge. In this context, not only chemists, engineers, or chemistry teachers but also all individuals who will be involved in different professional groups should be equipped with basic green chemistry knowledge. In this case, it is possible to widely integrate the understanding of green chemistry into all levels of education, from primary education to higher education and even post-graduate education (Eilks & Rauch, 2012; Nurbaity et al., 2016).

In order for individuals to acquire competencies for green chemistry, it is of great importance to spread educational practices for green chemistry fields. MacKellar et al. (2020) listed green chemistry competencies in their study. According to the researchers, an individual who has received green chemistry education will generally know the nature of chemicals and will have the necessary skills to choose which material is more sustainable. They will have the knowledge and skills to select or design safe chemicals that do not have a negative impact on the environment and human health. In addition to this knowledge, they will be able to carry out studies to reduce the footprint of chemicals on the environment in cooperation with other professional groups. In short, they will be able to have the necessary knowledge and design the necessary tools for the selection, design, comparison and evaluation of environmentally friendly and safe materials that serve human health in all chemical processes. Will be able to manage chemical processes in accordance with the green chemistry approach.

Science education is a discipline with various sub-disciplines such as physics, chemistry, biology, environmental education, astronomy, and earth science. Science education is not a field where only the information of these disciplines is presented. It is an active, dynamic, and, in short, a living science in which the knowledge of sub-disciplines is adapted to daily life by establishing interdisciplinary connections. It offers active, living by doing, and lifelong learning by providing students with the opportunity to apply their knowledge in depth and with laboratory applications (Abell et al., 2013). Due to its transdisciplinary nature and the sub-disciplines it contains, all kinds of applications and developments for environmental health are also a subject of science education (Abbasi et al., 2018; Kurnaz, 2019).

One of the fields of education where green chemistry studies are reflected is science education. Chemistry education, which includes knowledge and practices related to chemical science with innovative approaches, and environmental education, which includes knowledge and practices related to environmental health and sustainable development principles, are disciplines within the scope of science education. In this context, green chemistry practices should be provided to individuals in areas such as environmental education, chemistry education, and laboratory applications within the scope of science education (Karpudewan et al., 2009; Sjöström et al., 2016).

Andrew Dicks' studies can be given as an example of the integration of green chemistry into educational environments. Dicks (2009) aimed to make chemistry experiments carried out in laboratory applications in accordance with the principles of green chemistry. In this context, Dicks designed experimental setups in which water could be used as an alternative to solvents used in organic chemistry reactions and organized laboratory applications in accordance with the principles of green chemistry. Thanks to this arrangement, experiments that take a long time and carry risks such as potential exposure to chemicals can be carried out in a short time and in risk-free environments (Demir, 2017; Dicks, 2011).

Another example is the work of Julian R. Silverman. In his study, Silverman (2016) focused on the use of non-renewable energy resources, which is one of the biggest obstacles to ensuring environmental sustainability. In this context, Silverman suggested the use of biobased products that can be defined as sustainable in accordance with the principles of green chemistry instead of petroleum-based products in laboratory applications. The researcher designed experimental processes involving biobased products to be used in laboratories. In this way, he both drew attention to the use of renewable energies and transformed laboratory practices into a greener and more sustainable laboratory.

Another example of the reflections of green chemistry in laboratory studies is the preference for citral reactions as chemical selectors. Citrals are natural substances found in flower extracts that give off a pleasant odor. The preference of these substances in laboratory applications eliminates the bad odor and risk potential of chemical substances to be used as an alternative. Thus, students will be able to work with natural substances in their experimental processes, and laboratories will be safer and more sustainable (Cunningham et al., 2010).

The fact that the science of chemistry is based on experimentation poses many problems, such as the harm of chemical substances and wastes to human and environmental health. Both individuals and the environment need to be protected from the toxic effects of chemical substances. Although the foundations of the green chemistry concept that emerged in this context officially date back to the 1990s, it is a new concept for the education and training curricula of many countries. In our country, the foundations of chemistry education are laid with science education. The foundation of individuals' knowledge and skills about chemical processes and laboratory applications is shaped in the process of science education. This situation shows the importance of an innovative and effective science education. In this scope, it is very crucial to integrate green chemistry practices into science education not only in the field of chemistry or environmental education but also in all processes where chemicals are used and wastes are generated. Students who receive a green chemistry education integrated into science education will take care not to use chemicals harmful to human and environmental health throughout their lives. In addition, they will be able to access risk-free alternatives of these chemicals in the light of the knowledge they have through laboratory applications within the scope of science education. Thus, by preventing the use of harmful chemicals, they will contribute to human and environmental health and, moreover, to the efforts for a sustainable world.

References

Abbasi, S., Moeini, M., Shahriari, M., Ebrahimi, M., & Khoozani, E. K. (2018). Designing and manufacturing of educational multimedia software for preventing coronary artery disease and-its effects on modifying the risk factors in patients with coronary artery disease. *Electronic Journal of General Medicine*, 15(3). https://doi.org/10.29333/ejgm/85942

Abell, S. K., Appleton, K., & Hanuscin, D. L. (Eds.). (2013). *Handbook of research on science education*. Routledge.

Abdussalam-Mohammed, W., Ali, A. Q., & Errayes, A. O. (2020). Green chemistry: principles, applications, and disadvantages. *Chemical Methodologies*, *4*(4), 408-423. https://doi.org/10.33945/SAMI/CHEMM.2020.4.4

Anastas, P.T. & Williamson, T.C. (1996). Anastas, P. T., & Williamson, T. C. (1996). Green chemistry: an overview. In *Green Chemistry: Designing Chemistry For The Environment* (pp. 1-17). American Chemical Society. https://doi.org/10.1021/bk-1996-0626.ch001

Anastas, P. T. and Warner, J.C., (1998), *Green Chemistry: Theory and Practice*, Oxford University Press.

Anastas, P. T., & Warner, J. C. (2000). *Green chemistry: theory and practice*. Oxford University Press.

Anastas, P. T., Bartlett, L. B., Kirchhoff, M. M., & Williamson, T. C. (2000). The role of catalysis in the design, development, and implementation of green chemistry. *Catalysis Today*, *55*(1-2), 11-22. https://doi.org/10.1016/S0920-5861(99)00222-9

Anastas, P. T., & Kirchhoff, M. M. (2002). Origins, current status, and future challenges of green chemistry. *Accounts of Chemical Research*, *35*(9), 686-694. https://doi.org/10.1021/ar010065m

Anastas, N. D. ve Maertens, A. (2018). Integrating the principles of toxicology into a chemistry curriculum. In *Green Chemistry.* Elsevier, (pp.91-108).

Anastas, P. T., and Eghbali, N. (2010). Green chemistry: principles and practice. *Chemical Society Reviews*, *39*(1), 301-312. https://doi.org/10.1039/B918763B

Beach, E. S., Cui, Z., & Anastas, P. T. (2009). Green Chemistry: A design framework for sustainability. *Energy & Environmental Science*, *2*(10), 1038-1049. https://doi.org/10.1039/B904997P

Buckingham, S., & Turner, M. (Eds.). (2008). *Understanding environmental issues*. Sage Publications.

Clark, J., & Minhas, H. (2003). Looking forward to 2003 Phenomenal growth, but technology keeps Green Chemistry at the cutting edge. *Green Chemistry*, *5*(1), G1-G2. https://doi.org/10.1039/B300498H

Clark, J. H., Budarin, V., Deswarte, F. E., Hardy, J. J., Kerton, F. M., Hunt, A. J., Luque, R., Macquarrie D. J., Milkowski K., Rodriguez, A., Samuel, O., Tavener, S. T., White, R., & Wilson, A. J. (2006). Green chemistry and the biorefinery: a partnership for a sustainable future. *Green chemistry*, *8*(10), 853-860. https://doi.org/10.1039/B604483M

Cunningham, A. D., Ham, E. Y., & Vosburg, D. A. (2010). Chemoselective reactions of citral: green syntheses of natural perfumes for the undergraduate organic laboratory. *Journal of Chemical Education*, *88*(3), 322-324. https://doi.org/10.1021/ed100539m

Dicks, A. P., & Batey, R. A. (2013). ConfChem Conference on Educating the Next Generation: Green and Sustainable Chemistry - Greening the Organic Curriculum: Development of an Undergraduate Catalytic Chemistry Course. *Journal of Chemical Education*, *90*(4), 519-520. https://doi.org/10.1021/ed2004998

Dicks, A. P., & Hent, A. (2015). Atom economy and reaction mass efficiency. *Green Chemistry Metrics: A Guide to Determining and Evaluating Process Greenness*, 17-44. https://doi.org/10.1007/978-3-319-10500-0_2

Dicks, A. P. (Ed.). (2011). *Green organic chemistry in lecture and laboratory*. CRC Press.

Demir, B. (2017). *Concept of green chemistry and adaptation of general chemistry laboratory experiments to the principles of green chemistry*. (Master's Thesis). Inonu University.

Eilks, I., & Rauch, F. (2012). Sustainable development and green chemistry in chemistry education. *Chemistry Education Research and Practice*, *13*(2), 57-58. https://doi.org/10.1039/C2RP90003C

Environmental Protection Agency (EPA). (2020). Definition of green chemistry. [https://www.epa.gov/greenchemistry/basics-green-chemistry], Erişim tarihi: 29 Kasım 2024.

Erökten, S. (2006). *Different evaluations related with teaching "green chemistry" topic in chemistry education.* (Doctoral Thesis), Hacettepe University.

Gerçek, Z. (2012). The new color of chemistry: Green chemistry. *Journal of Higher Education and Science, 2*(1), 50-53. https://doi.org/10.5961/jhes.2012.033

Hjeresen, D. L., Boese, J. M., & Schutt, D. L. (2000). Green chemistry and education. *Journal of Chemical Education*, *77*(12), 1543. https://doi.org/10.1021/ed077p1543

Hjeresen, D. L., Kirchhoff, M. M., & Lankey, R. L. (2002). Green chemistry: Environment, economics, and competitiveness. *Corporate Environmental Strategy*, *9*(3), 259-266. https://doi.org/10.1016/S1066-7938(02)00068-4

Horvath, I. T., & Anastas, P. T. (2007). Innovations and green chemistry. *Chemical reviews*, *107*(6), 2169-2173. https://doi.org/10.1021/cr078380v

Karpudewan, M., Ismail, Z. H., & Mohamed, N. (2009). The integration of green chemistry experiments with sustainable development concepts in pre-service teachers' curriculum: Experiences from Malaysia. *International Journal of Sustainability in Higher Education, 10*(2), 118–135. https://doi.org/10.1108/14676370910945936

Keinan, E. (2021). "Think Globally, Act Locally" An interview with Prof. Ryōji Noyori. *Asia Chem Magazine*, *2*(1), 88-95. https://doi.org/10.51167/acm00028

Keleş, R. & Hamamcı, C., (2002). *Çevre bilim*, İmge Kitabevi.

Kerton, F. M., & Marriott, R. (2013). *Alternative solvents for green chemistry*. Royal Society of chemistry.

Kottappara, R., Palantavida, S., & Vijayan, B. K. (2020). Reduce derivatives. In *Green chemistry and applications* (pp. 152-176). CRC Press.

Kurnaz, Ş. (2019). *Comparison of science literacy and field knowledge competences of prospective science teachers: the case of Suleyman Demirel University-Mehmet Akif Ersoy University* (Master's thesis) Suleyman Demirel University.

Krasnodębski, M. (2022). Lost green chemistries: history of forgotten environmental trajectories. *Centaurus*, *64*(2), 509-536. https://doi.org/10.1484/J.CNT.5.131246

Linthorst, J. A. (2010). An overview: origins and development of green chemistry. *Foundations of chemistry*, *12*, 55-68. https://doi.org/10.1007/s10698-009-9079-4

Liu, Q., Gong, D. & Chen, M. (2018). Applying virtual reality to study the effects of environmental education on college students' ethics and environmental literacy. *Eurasia Journal of Mathematics, Science and Technology Education, 14*(6), https://doi.org/10.29333/ejmste/85937

Maxim, L. (2023). The birth of green chemistry: a political history. *Science, Technology, & Human Values*, *50*(1), 144-168. https://doi.org/10.1177/01622439231203063

MacKellar, J. J., Constable, D. J., Kirchhoff, M. M., Hutchison, J. E., & Beckman, E. (2020). Toward a green and sustainable chemistry education road map. *Journal of Chemical Education, 97*(8), 2104-2113. https://doi.org/10.1021/acs.jchemed.0c00288

Mellor, K. E., Coish, P., Brooks, B. W., Gallagher, E. P., Mills, M., Kavanagh, T. J., Simcox, N., Lasker, G. A., Botta, D., Voutchkova-Kostal, A., Kostal, J., Mullins, M. L., Nesmith, S. M., Corrales, J., Kristofco, L., Saari, G., Steele, W. B., Melnikov, F., Zimmerman, J. B., & Anastas, P. T. (2018). The safer chemical design game. Gamification of green chemistry and safer chemical design concepts for high school and undergraduate students. *Green Chemistry Letters and Reviews, 11*(2), 103–110. https://doi.org/10.1080/17518253.2018.1434566

Morales, C. G., Castolo, A. A., & Rodriguez, M. A. (2020). Designing Safer Chemicals. In *Green Chemistry and Applications* (pp. 60-83). CRC Press.

Mulholland, K. L., Sylvester, R. W., & Dyer, J. A. (2000). Sustainability: waste minimization, green chemistry and inherently safer processing. *Environmental Progress, 19*(4), 260-268. https://doi.org/10.1002/ep.670190413

Murphy, M. A. (2020). Early industrial roots of green chemistry – II. International "pollution prevention" efforts during the 1970's and 1980's. *Substantia 4*(2): 15-57. https://doi.org/10.13128/Substantia-894

Nurbaity, Rahmawati, Y. & Ridwan, A. (2016). Integration green chemistry approach in teacher education program for developing awareness of environmental sustainability. In ASEAN Comparative Education Research Network Conference. November.

O'Connell, A. (1995). Benign by design, alternative synthetic design for pollution prevention, Anastas Paul T., Farris Carol A.(Eds.), in: Office of Pollution Prevention and Toxics, US Environmental Protection Agency, ACS Symposium Series, 577, American Chemical Society, Washington DC (1994), p. 195.

Sheldon, R. A. (2008). Why green chemistry and sustainability of resources are essential to our future. *Journal of Environmental Monitoring*, *10*(4), 406-407. https://doi.org/10.1039/B801651H

Sheldon, R. A. (2018). Metrics of green chemistry and sustainability: past, present, and future. *ACS Sustainable Chemistry & Engineering*, *6*(1), 32-48. https://doi.org/10.1021/acssuschemeng.7b03505

Silverman, J. R. (2016). Biobased organic chemistry laboratories as sustainable experiment alternatives. *Journal of Chemical Education*, *93*(10), 1679-1681. https://doi.org/10.1021/acs.jchemed.5b00706

Sjöström, J., Eilks, I. & Zuin, V.G. (2016). Towards eco-reflexive science education. *Science & Educ*ation, *25*, 321–341 https://doi.org/10.1007/s11191-016-9818-6

Sogut, O., & Çelebi, B. (2020). Cleaner Analyzes: Green Chemistry. *Duzce University Journal of Science and Technology* , *8*(1), 160-175. https://doi.org/10.29130/dubited.579987

Tang, S. L., Smith, R. L., & Poliakoff, M. (2005). Principles of green chemistry: productively. *Green Chemistry*, *7*(11), 761-762. https://doi.org/10.1039/B513020B

Trost, B. M. (1995). Atom economy—a challenge for organic synthesis: homogeneous catalysis leads the way. *Angewandte Chemie International Edition in English*, *34*(3), 259-281. https://doi.org/10.1002/anie.199502591

Ukaogo, P. O., Ewuzie, U., & Onwuka, C. V. (2020). Environmental pollution: causes, effects, and the remedies. In *Microorganisms for sustainable environment and health* (pp. 419-429). Elsevier. https://doi.org/10.1016/B978-0-12-819001-2.00021-8

Verma, S., Verma, S., Agrwal, A., & Kumar, S. (2024). Use of renewable feedstocks for chemical synthesis. In *Green chemistry approaches to environmental sustainability* (pp. 219-237). Elsevier.

Wilson, M. P., & Schwarzman, M. R. (2009). Toward a new US chemicals policy: rebuilding the foundation to advance new science, green chemistry, and environmental health. *Environmental health perspectives*, *117*(8), 1202-1209. https://doi.org/10.1289/ehp.0800404

Yayayürük, A. E., & Yayayürük, O. (2019). Applications of green chemistry approaches in environmental analysis. *Current Analytical Chemistry*, *15*(7), 745-758. https://doi.org/10.2174/1573411015666190314154632

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