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Green Economy Supported by Green Chemistry

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Abstract

We are witnesses of excessive depletion of natural resources, climate change and a loss of biodiversity. Water, air, soil, light and noise pollution is increasing. At the end the quality of life is worsening as well. Interdisciplinary approach is needed. Economy and chemistry are two different scientific areas, which facing environmental challenges develop divergently. The results are that we have green economy and green chemistry; we deal with complex problems sharing our knowledge and supporting each other. Green chemistry is a new paradigm that provides solutions to contemporary environmental, ecological and sustainable challenges. The aim of the paper is to present approaches of green economy and green chemistry, collaborations between them and integrative effort in solving environmental challenges toward sustainability. The goal is to present examples of green business based on green chemistry. Methodology encompasses case studies of companies with green business. This paper contributes to existing research in three ways: it spreads knowledge and good business experiences, it shows long term benefits and it raises awareness of a paradigm shift towards ecology and sustainability.

Keywords: Green Chemistry, Green Business, Interdisciplinary Approach, Sustainability, Green Growth

1. Introduction

Interdisciplinary approach involves the combining of two or more academic disciplines into one activity, e.g. research project. It offers a large potential for new perspectives, new inventions, and for researchers more opportunities to publish (Grebel *et al.* 2018). Scientists from different areas are coming together to solve problems. Eco- and environmental innovations are result of collaboration between experts from different fields and demarcation between environmental and technology policies gets more and more blurred (Crespi *et al.* 2015). Green innovation is a basis for green entrepreneurship (Ebrahimi and Mirbargkar, 2017). Moreover, design of environmental policies foster eco-innovation (Bitat, 2017). Sustainability is an integrative, holistic and long-term oriented approach that advocates balance between economic, social and ecological dimensions of economy. It is based on innovations and new inventions. Green economy supported by green chemistry is a process of innovation and transformation toward sustainability.

Noyori (2005) stressed that in the 21st century, the field of chemistry will face more than just academic challenges. Chemistry, together with physics, biology, geography and geology, develops thanks to man's curiosity and his need for answers to questions about his origin, evolution, role and place in nature and universe (Zidak, 2014). Green chemistry is a term which has been used for the last three decades. It can be simply defined as the development and production of chemical products and the establishment of procedures that can replace or abandon the generation of dangerous products. According to the EGLE (2009) and Thomas *et al.* (2009), the scope and boundaries of a Green Chemistry Program should consider all the stages of the life cycle of a chemical, should focus on "hazard reduction" as the primary impact category of interest in each life cycle stage with a focus on the design stage. Other life cycle impacts of innovation should also be considered. Finally, it should reduce hazards to human and ecosystem health. Green chemistry considers (Young, 2011) where the chemicals come from, how they are made, how they are used and where they end. The aim is to avoid any negative impact on human health and the environment.

The main purpose of this paper is to discover the multidimensionality of green chemistry and explore how green chemistry can support green business. Moreover, we want to analyze green chemistry, its components, evolution and future perspectives and to reveal how green chemistry contributes to economy and sustainability. In addition, we present examples of collaboration between green chemistry and the green economy. We illustrate how green chemistry already supports green business with great strides toward sustainability.

2. Green chemistry evolution

The term 'Green chemistry' was coined in the US Environmental Protection Agency (EPA). In 1993 the EPA officially adopted the name 'US Green Chemistry Program' which served as a focal point for activities within the United States. This does not mean that research on green chemistry did not exist before the early 1990s, merely that it did not have the name (Sheldon, 2008).

Over the last 25 years, the concept of green chemistry, in particular, the principle of designing synthetic methods to maximize the incorporation of all raw materials in the product, and the underpinning metrics, atom economy and the E factor have been widely embraced by industry and academia worldwide (Sheldon, 2016). Green chemistry is also known as sustainable chemistry (United States Environmental Protection Agency, 2017).

2.1. Components of green chemistry

Green chemistry is a new paradigm that provides solutions to contemporary, ecological and sustainable challenges. The term green chemistry is often used for chemical pathways which respect and preserve resources and the environment. The goal is to avoid unwanted byproducts by choosing appropriate reaction pathways and chemical agents (Theisen, 2018). According to Theisen (2018), Sheldon (2016) and Thomas *et al.* (2009); the main points or components of green chemistry can be presented in Table 1.

Sheldon (2008, p. 406) pointed out the following: "It is important to stress that green chemistry addresses both chemical products and the processes by which they are manufactured. The emphasis is clearly on design of greener products and processes. It is purposely said greener rather than green as there are many shades of green. Green chemistry embodies two components: (i) efficient utilization of raw materials and the elimination of waste, and (ii) health, safety and environmental aspects of chemicals and their manufacturing processes." According to Sheldon (2008), green chemistry eliminates waste at source. It is primary pollution prevention not end-of-pipe solutions. Waste remediation may be useful and necessary in the short term but it does not constitute green chemistry.

Table 1. Green chemistry's components

Design	chemical products and processes that reduce or eliminate the use or generation of hazardous substances
	applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal
Use	utilizes raw materials, eliminates waste and avoids the use of toxic and/or hazardous reagents and solvents
	concerned with the prevention of pollution by waste minimization and the avoidance of toxic and hazardous substances
Effort	to minimize expenses of energy and chemicals
	to use harmless reactants, alternative solvents and new pathways of synthesis

Source: Authors' own preparation

2.2. Basic principles of green chemistry

Green chemistry reduces or eliminates the need for and generation of hazardous materials during the manufacture, design, and application of chemistry (Thomas *et al.* 2009). It is based on the 12 principles of green chemistry as follow:

1. avoid pollution: chemical syntheses, processes and reactors need to be designed to avoid dirt and contamination;
2. design safer chemical products: emphasize effective products that are less toxic than comparable materials;
3. produce less hazardous substances: create and use substances that pose no risk to humans and the environment;
4. use renewable raw materials as much as possible;
5. use of catalysts instead of stoichiometric reagents by minimization of the reaction partners;
6. avoid unnecessary intermediate steps in chemical processes;
7. maximize the atom efficiency: design syntheses and reactions so that no, or only a few atoms or molecules of the initial reagents remain, or, so that no unwanted dangerous substances remain;
8. use safe solvents and safe reaction conditions: if possible, avoid the use of adjuvants;
9. increase energy efficiency: if possible manage reactions and processes at room temperature;
10. produce chemicals and side products: these can be degraded without harming the environment;
11. control all operations by real time management to prevent pollution and contamination, which will help to avoid waste;
12. minimize the risk of accidents (Anastas and Warner, 1998).

These principles of green chemistry actually reflect a broad spectrum of green chemistry. It is important to note that the scope of green chemistry and engineering principles go beyond concerns over hazards from chemical toxicity. Green chemistry includes energy conservation, waste reduction, and life cycle considerations such as the use of more sustainable or renewable feedstocks and designing for end of life or the final disposition of the product.

3. Sustainable chemistry

Sustainable development has been defined in many ways, but the most frequently quoted definition is from United Nations (1987, pp. 41) as "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs".

Ensuring environmental sustainability is one of the eight Millennium Development Goals promoting integration, among other things, of the principles of sustainable development into country policies and programs to reverse the loss of environmental resources (United Nations, 1987). Chemists understand sustainable chemistry as the use of different methods to carry out chemical reactions without burdening future generations. Moreover, sustainable chemistry is about using and developing technologies that use fewer raw materials and energy, maximize the use of renewable resources, and minimize or eliminate the use of hazardous chemicals (Beller, 2008).

The Society of German Chemists (Germ. Gesellschaft Deutscher Chemiker, 2019) advocates a holistic perspective of products and processes through the whole life cycle (from the "cradle to the grave"). In this sense, sustainable chemistry means exploring the use of material resources and their transformation without harming future generations. New developments in the field of sustainability make chemistry a central problem solver of the next decades (Nachhaltige Chemie, 2007).

3.1. Green chemistry's contribution to sustainability

The ecological term of sustainability is always found in connection with green chemistry (Industry Search, 2016). According to the Federal Environment Agency (Germ. Umweltbundesamt), the concept of sustainable chemistry aims to connect preventive protection of the environment and health with an innovative economic strategy that also leads to more employment. In collaboration with the Organization for Economic Co-operation and Development (OECD), this agency elaborated and specified in depth criteria for a sustainable chemistry in 2004 focused on qualitative development, quantitative development, comprehensive life-cycle monitoring, action instead of reaction and economic innovation (Umweltbundesamt, 2018). Key points of green chemistry's contribution to sustainability are presented in Table 2.

Table 2. Green chemistry's contribution to sustainability

preserving	**reducing**	**avoiding**
resources human health environment	greenhouse gases risk of chemicals consumption of materials and solvents energy use	waste pollution unwanted byproducts
general perspectives		
choosing appropriate reaction pathways and chemical agents increasing safety improving process efficiency saving costs		

Source: Authors' own preparation

"We believe that green chemistry is a key to mastering these challenges while building a sustainable future" (Young, 2011, p. 22). We can summarize, if the chemistry is a problem, then the green chemistry is a solution.

3.2. Future perspectives of green chemistry

There are a few directions of green chemistry's future development: further evolution of green chemistry, meaningful metrics and education. As for the evolution of green chemistry, it has first spread to the area of design for the environment and then to sustainable chemistry, with green chemistry remaining in the core. Designing for the environment improves environmental and human health and increases product performance and market competitiveness. The focus is on finding sustainable solutions to identify materials of concern. In essence, designing for the environment represents the application of green chemistry in practice (Thomas *et al.* 2009).

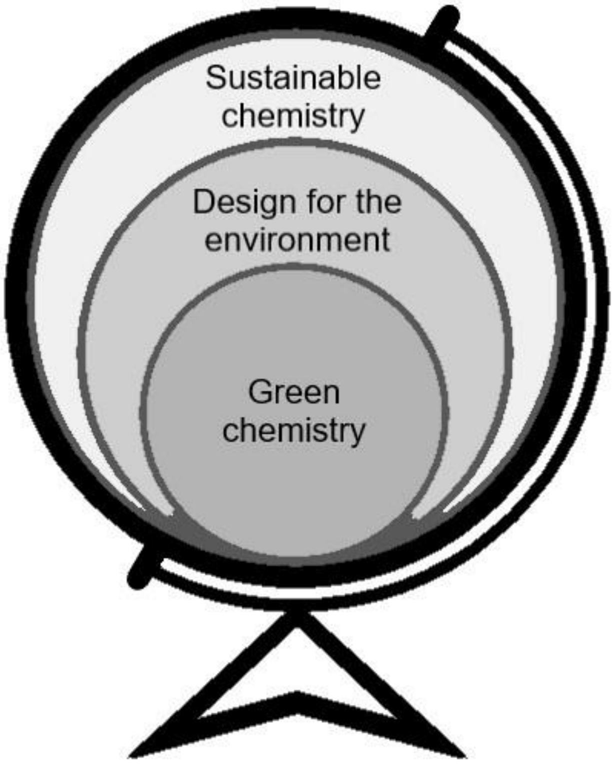

Figure 1. Green chemistry's development
Source: Authors' own preparation

While design for the environment is focused on present environmental and human health, sustainable chemistry is focused on future and long term environmental and human health. Figure 1 presents the evolution of green chemistry using Venn's diagram and shows the relationship and the importance of green chemistry for the planet Earth.

In our opinion, the fundamentals of sustainable chemistry emphasize the connection between today's decisions and tomorrow's consequences. Another future perspective is to find meaningful metrics for sustainability and green chemistry. They are important for comparing the different shades of green, and reliable methods for monitoring the environmental footprint of chemical products are both necessary and complementary (Sheldon, 2008). Further research and development in academia, industry and policy environments in order to serve and support decision making processes toward sustainability is needed (De Soete *et al.* 2017). The evolution of green chemistry, metrics and education opens very important new perspectives with a lot of open questions. There are many challenges regarding applications of green chemistry in different fields, for example in the economy and business.

4. Green business based on green chemistry

There is increasing pressure from both society and governments for chemistry-based industries to become more sustainable through development of eco-friendly products and processes that both reduce waste and prevent toxic substances from entering the environment (Akram, 2015). Although the implementation of green chemistry relates to investment, ecological and sustainable benefits are much higher than the financial costs (Sheldon *et al.* 2007).

There are guidelines to promote green practices, create green economic opportunities, and move national policy forward; firstly, defining and presenting examples of green chemistry and design for the environment. After that, presenting options for states to use, such as the development, collection, and dissemination of information, economic incentives, recognition programs, and regulations and policies. Next step is presenting roles for education institutions, a vital partner in this effort and finally, identifying available resources and tools (Thomas *et al.* 2009).

New business profits are attributable to green chemistry if costs are saved by avoiding waste and pollution. This reduces the risk of chemicals and increases safety. Green chemistry has also been shown to reduce energy consumption and greenhouse gases, improve process efficiency and, in some cases, reduce the consumption of materials and solvents. That is why green chemistry is good for the business (Young, 2011). Nevertheless, some results indicate that whether 'it pays to be green' or not, depends on firm size (Boring, 2019).

The American Chemistry Council estimates that each job in chemistry generates 5.5 additional jobs elsewhere in the economy (Thomas *et al.* 2009). The Association of the Chemical Industry (Germ. Verband der Chemischen Industrie) has gone a step further and established Chemistry^3 (Germ. Chemie^3) with the aim of anchoring sustainability in the chemical industry as a main leading idea. Chemistry^3 thus encompasses all three dimensions of sustainability; the economy, society and ecology (Chemie^3, 2018).

Increased interest in green and sustainable growth is stimulating a much needed move from the traditional linear flow of materials in a 'take-make-use-dispose' economy, to a greener, circular one which seeks to eliminate waste through deliberate design of products, processes with resource efficiency and recycling in mind. This philosophy forms the basis of the European Commission's "Roadmap to a resource efficient Europe" (Sheldon, 2016).

Commoner (1971) already recognized the linear vs. circular economy issue in the 1960s. The necessary transition from an unsustainable linear economy to a greener circular one is hampered by the fact that economic assessments are not being conducted on a level playing field (Sheldon, 2016). There are numerous examples of collaboration between green chemistry and the green economy. In Table 3, three examples are shown to illustrate how green chemistry supports green business.

Table 3. Examples of green business based on green chemistry

Production of biogas from manure
The volume of produced biogas and energy generated depends on the type of animal. Research has proven that utilizing manure from 120 cows can produce enough biogas to power a 50 kW engine, which is enough to supply a smaller village with electrical energy. The generation of electrical energy and production of high-quality manure through anaerobic digestion also contributes to the reduced pollution of the environment.
Storage of CO_2 in deep saline formations
Deep saline caverns are geological formations of porous rock containing sea water and as such, they present a potential for the highest capacity of CO_2 sequestration. Seeing as how these formations are present throughout the world, they are also the most easily accessible means of CO_2 sequestration. However, Norway is the only country in the world currently implementing this method. Utilizing a single massive natural gas extraction pump, natural gas (containing 9% CO_2 volume) is stored in containers for later use in industrial purposes, while CO_2 is filtered out and stored in the aforementioned deep saline formations (roughly 800 m below the seabed), where the geological formations prevent further CO_2 emission into the atmosphere. This method of CO_2 storage has significantly decreased CO_2 emissions in Norway to only 3%, which is by far the closest anyone has come to the commercial standard of a minimal 2.5% CO_2 emission. It is estimated that utilizing this method for the duration of this project could store approximately 20 Mt CO_2.
Bioethanol as a fuel source for pollutant-free motor vehicles
Brazil is the leading country in the production and usage of ethanol for motor vehicles, producing more than 15 billion liters yearly. Approximately 15% of all vehicles in Brazil are powered by pure ethanol, with another 40% roughly using 20% ethanol blended gasoline. Ethanol production in Brazil began in order to decrease the country's dependence on foreign oil and to open an additional market for the local sugar. In the United States, ethanol blends make up roughly 9% of total yearly gasoline sales.

Source: Authors' own preparation based on European Biogas Association (2016), Sormaz (2014), and Vinčić *et al.* (2011)

Green chemistry and the green economy, design for the environment and sustainable chemistry with sustainable economy are challenges for state governments as well. State governments, environmental and health ministries, non-governmental organizations and universities are called to promote, stimulate and apply the sustainable paradigm by economic incentives such as the environmental tax, investment tax credits, low-interest loans, loan guarantees, or subsidies for green chemistry manufacturing equipment or products. More specifically, green chemistry can promote existing economic development projects such as industrial parks, brownfields, or low-impact development (Thomas *et al.* 2009).

State governments have a unique opportunity to promote safer chemical processes and products and the growth of the green economy by advancing green chemistry and design for the environment (Thomas *et al*. 2009).

5. Conclusion

Interdisciplinary approach is always challenging. It builds bridges between different scientific fields offering new perspectives, innovations and inventions. Green chemistry with its multidimensionality can support and enrich green business. There are many examples of collaboration between them. Green chemistry encompasses chemical products and processes by which they are manufactured, and it refers to all chemical disciplines and areas. It is not a separate sub discipline, but a system approach that permeates all chemistry.

Green chemistry is sustainable in the sense that it serves the needs of today's generation without endangering the possibilities of future generations. In this paper, we analyzed the evolution of green chemistry; we explored and defined design, use and effort as main green chemistry's components. Green chemistry contributes to sustainability in several ways. We stressed preserving, reducing and avoiding as three main activities. We expounded general perspectives as well as more specific ones such as choosing appropriate reaction pathways and chemical agents, increasing safety, improving process efficiency and saving costs. Sustainable chemistry is the broadest view that includes design for the environment, both based on green chemistry. The differences between green chemistry, design for the environment and sustainable chemistry are qualitative and quantitative in nature. The common starting point is environmental and human health, with graded extension of content and time frame. We concluded that meaningful metrics and education are key perspectives in the development of sustainable chemistry.

Green chemistry and the green economy are blending together. Presented examples prove their successful collaboration. There are challenges for state governments, environmental and health ministries, non-governmental organizations and universities to promote and implement principles of green chemistry through design for the environment toward sustainable development.

Contributions of our paper are several. We explore interdisciplinary collaboration between green economy and green chemistry stressing large potential that includes benefits for all. It spreads out the knowledge and good business practice of green chemistry, it shows long term benefits for ecology through design for the environment and it raises awareness of a paradigm shift toward sustainability.

More research is needed on how green chemistry can support the green economy, and vice versa, both theoretically and empirically. It is the beginning but there are already respectable results. Still, further collaboration among academic and business community is needed and expected.

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