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Commentary

Sustainable chemistry and chemical processes for a sustainable future

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Green Chemistry vs. Sustainable Chemistry

Green chemistry principles have revolutionized the conventional paradigm of chemical synthesis, process design and reaction chemistry and engineering advancements [1]. The focus of these principles is to reduce wastes, increase yields and reduce non-renewable energy and material input along with environmentally conscious design of chemical reactions and products (see Fig. 1). Sustainable chemistry was also introduced to provide a broader understanding of the need for novel attitude in chemical synthesis. While green chemistry is at the center of the sustainable chemistry, it goes beyond the "greenness" to promote "Sustainable Production". Sustainable chemistry focuses on increasing the product recovery (diversifying the products), increasing byproduct reuse and recycling, improving longevity of resources including raw materials, and mechanical processes and their performance. It also focuses on process and environmental safety and economic, ecological and social benefits derived from fundamental processes. It is based on an "eco-friendly" design that ensures maintenance and continuation of an ecologically sound process development [2]. It includes both tangible and intangible benefits that would otherwise be not possible with green chemistry approach.

The twelve principles of green chemistry that when used in the design, development and implementation of chemical products and processes, enables scientists to protect and benefit the economy, people and the planet. The ultimate goal is to physically reduce the quantities of chemicals that have a negative impact on human health and the environment [3]. Sustainable chemistry is defined as the part of chemistry which is essential to a sustainable society with a view to product design, manufacturing, consumption of resources, health and safety at work, economic success and technical innovation - not only in industrialized nations but in emerging and developing countries as well. Sustainable chemistry thus extends far beyond the application of ecological principles in chemical production. Table 1 lists the main differences in green chemistry and sustainable chemistry concepts. Sustainable chemistry, in general, is an ongoing activity that takes novel approaches to accomplish and institute green chemistry at its best to promote sustainability in human development.

Promoting sustainable chemistry and chemical process development

Although green chemistry is at the center of the sustainable chemistry and chemical process development, "green" does not mean "sustainable". In other words, not all green processes are sustainable processes. Economic, environmental, and ecological aspects should be the starting points for any chemistry, reaction design and process development (see Fig. 2). It may not be possible to develop chemical processes without the use of the most basic and essential commodities, water and energy [4]. These commodities are also fundamental to our existence and sustainable development. Therefore, a sustainable process should generate products that feed into other beneficial processes thus allowing a continuum of material and energy flows necessary to establish environmental, ecological and economic sustainability.

Sustainable chemistry and chemical process development should be monitored closely. For example, numerous chemicals are routinely used in production processes and to develop new products. Chemical substitution and or reduction in a process may result in new issues and risks associated with them which needs to be comprehensively studied. This evaluation should not only be based on the risk and regulatory based requirements but also consider physical and psycho-social risks associated with changes in work patterns [5]. There is a need for tools to more rapidly assess chemicals, possibly by using chemical sensors, in a real time monitoring scheme to eliminate formation of hazardous substances. Monitoring also allows for optimizing the efficient use of reagents

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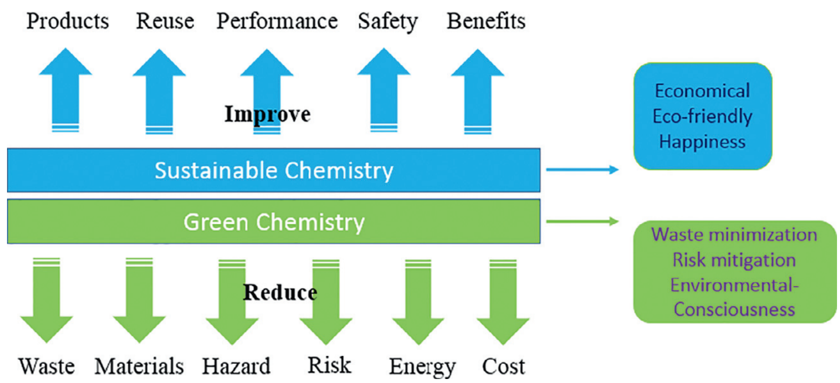

Fig. 1. Green chemistry vs. sustainable chemistry.

Table 1
Green chemistry vs. sustainable chemistry.

Green chemistry	Sustainable chemistry
Reduce waste	Utilize waste
Pollution free	Ecologically friendly
Renewable materials	Responsible resource utilization
Avoid byproducts	Enhance spectrum of products
Reduce costs	Increase benefits
Environmentally-conscious design	Eco-friendly design and enterprise

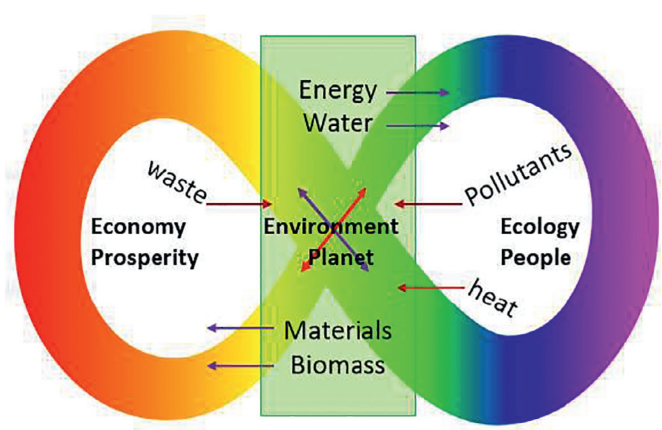

Fig. 2. Efficient use of natural resources to achieve sustainable economy and healthy ecology and environment.

and permits determination of the composition of waste and effluents and determine their potential beneficial uses [6].

Sustainable chemistry and chemical process development should aim to: (1) improve the harvesting and processing of natural resources, (2) develop replacement and substitute chemicals and materials for those that are scarce, toxic, and/or expensive, (3) extend the lifetime of materials through improved durability, (4) reduce energy consumption through improved catalysis, and (5) discover low-energy means of recycling, repurposing, recovering, and reusing chemicals and materials [7].

The following can be considered to promote sustainable chemistry [8,9]:

- Chemicals and materials should be synthesized using renewable feedstock supplies rather than petroleum derived molecules.
- Reactions should be designed to promote highly selective and active catalysts, i.e. consider tandem reactions and tandem catalysts which do not produce isolating intermediates, undesired byproducts, and do not require toxic reagents.
- Single solvent chemistry with tunable properties for multiple types of chemical reactions should be used rather than a cocktail of solvents for each reaction type.
- Slow and time consuming reaction discovery and process optimization processes should be replaced by in situ spectroscopic methods for real time monitoring of reactions over timescales from nanoseconds to hours.
- Computational approaches and tools should be pursued as much as possible to avoid unnecessary screening of large number of candidate materials for new product or process development.
- Modular micro-reactor design and configurations should be developd in lieu of specialized macro-reactors for rapid assembly in new process development.
- Complex and energy-intensive separation and purification processes should be replaced by highly selective, nanomaterial based separations for distillation, extraction, crystallization and chromatography.

Looking forward: chemistry attitude and chemical education

Major changes are essential to institute sustainable chemistry practices as the relationship between scientific and industrial chemistry on the one hand and society on the other hand has undergone fundamental changes over the past few decades. This introduces two basic elements related to scientific and non-scientific factors [10]. The two elements can be coordinated by bringing a sea change in the chemical community (both through attitude and education involving ethics and science) which has to start with educating the new generation of chemistry [11]. The chemistry or chemical education should broaden the understanding of the influences of chemistry on the environment, ecology and economic development. Collins [11] suggests that sustainable chemical education should be based on environmental-conscious and ethical design to promote transparent and accomplishable goals not motivated by greedy business needs but by human and environmental health. United States Environmental Protection Agency (USEPA), for example, conducts P3 (People, Planet and Prosperity) competition to promote sustainable chemistry and design of products [12,13] (see Fig. 3). This program encourages and fosters the scientific and engineering thinking among the college students to design products that benefit people, promote prosperity and protect the planet by designing environmental solutions that help build a sustainable future. The program considers challenges related to water, energy, food, built environment and materials and chemicals faced in both developed and developing countries. The agency also instituted a Presidential Green Chemistry Challenge Award to promote advances in green and sustainable chemistry frontiers [14].

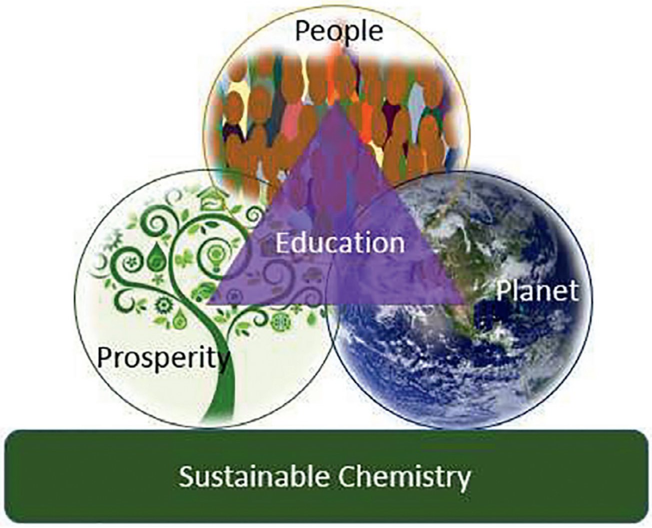

Fig. 3. Chemical education as a center piece to promote sustainable chemistry.

Chemistry attitude and education should be expanded beyond the laboratory walls and consider to embrace the global community and its prosperity. Sustainable chemistry and green chemistry approaches should be collectively explored in an integrative way and exploited to develop new approaches such as innovative business models, ensuring the coherent and comprehensive development of research, policies and practical approaches [3]. Education and outreach should be considered an integral part of this effort. Because issues related to people, planet and prosperity cannot be addressed in isolation but a multidisciplinary approach is crucial for creating a sustainable future [15].

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