

The Long Term Benefits of Applying Green Chemistry in Manufacturing

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Abstract

Implementing green chemistry in manufacturing may involve high initial costs; however, the long-term advantages are far more valuable than those of traditional methods of chemical processes. This research mainly focused on the influence of green chemistry, especially on industry, and the efficient use of energy. The paper introduces the roles of different types of green technologies, for example, sustainable fuels and solvents, which could replace those toxic ones, analyzes their use in reducing the carbon cycle, and examines the reliability of fossil fuels. By doing an analysis on multiple chemical methods, this research has shown how green chemistry promotes sustainable development and emphasizes the importance of the development in this field so that it could contribute to the technology in the future.

Keywords

Green Chemistry, Pollution Prevention, Sustainability, Catalysis, Energy Efficiency

1 Introduction

Starting from the 1940s, the world has grown significantly within the development of industry and material science. A lot of new technologies and new production modes were designed. However, these changes have caused significant environmental pollution such as heavy metal pollution, industrial pollution and excessive energy consumption.

Starting from the 1960s and 70s, more and more people have become aware of the environmental damage that chemical companies and the usage of chemical pesticides have brought. This attitude has made humans and companies realize that the industry should predict its process and the damage its products may have, and they should aim to limit those impacts instead of facing disasters passively. In the 1990s, the congress passed the Federal Pollution Prevention Act of 1990, which instructed the industry to take a pollution prevention approach (Boerner).

In 1998, in response to the call, Paul Anastas, an Environmental Chemistry professor at Yale University, and John Warner, a professor at UMass Boston, introduced

the concept of green chemistry in response to escalating environmental concerns. Green chemistry is not a specific reaction; it is a frame that keeps industry and its pollutants in it. Green chemistry encompasses a series of practices focused on developing, implementing, and applying materials that minimize hazards to human health and the environment following alongside the twelve principles of green chemistry. By adhering to the twelve principles of green chemistry, companies can not only promote sustainable development, but also enhance operational efficiency, particularly in production, while reducing their negative environmental impact. This raises an important question: What are the long-term benefits of implementing green chemistry in manufacturing, especially when compared to the challenges posed by high initial costs relative to traditional chemical processes?

This article argues that while adopting green chemistry may require significant upfront investment, the long-term benefits are considerably more valuable than those associated with conventional chemical methods.

2 The Economic Case for Pollution Prevention

It is more cost-effective to prevent environmental pollution than to clean up the damage caused by traditional chemical methods. For instance, a study conducted in 2022 highlights the substantial economic impact of air pollution in various countries. According to the research from UNECE:

"...in nearly half (26) of 56 countries in the Pan-European region and North America, the current monetary damage cost to health, ecosystems and the economy due to ambient air pollution corresponds to over 5% of GDP. In at least 6 countries, the damage is more than 10% of GDP. To compare, the average cost of an optimal air pollution strategy is estimated to be 0.01–0.02% of GDP" (UNECE).

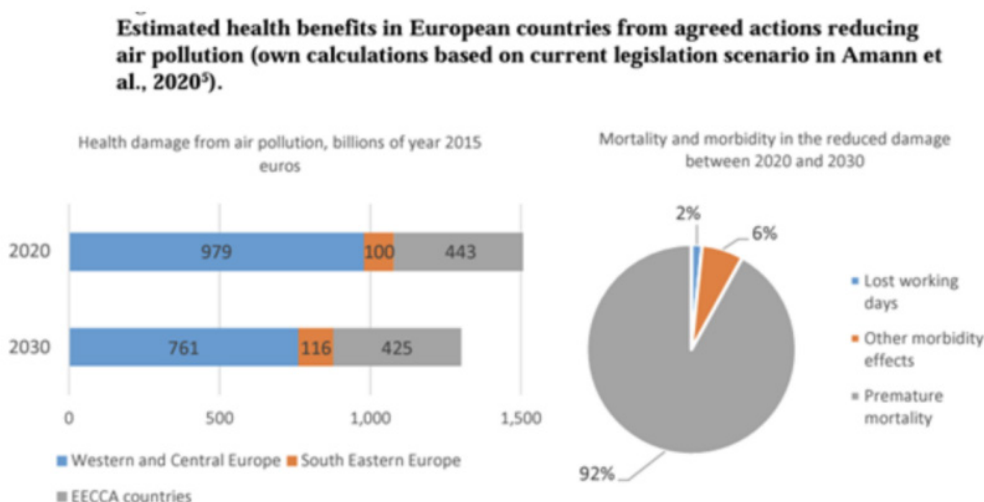


Figure 1. Economic Damage from Air Pollution as Percentage of GDP (Source: UNECE, 2022)

This quote highlights the significant impact of air pollution on the economy in Europe and North America. The statistics of 5% GDP in damage related to pollution in nearly half of the countries surveyed and 10% GDP in over six countries are severe enough that cannot be ignored. These findings suggested that the long-term economic advantages are more beneficial than the costs of mitigation efforts.

Not only companies, but universities have also realized the importance of preventing environmental pollution, especially the significant amount of money it could save. Kansas State University's E2/P2 intern program is a notable example: "Since 2006, implementation of the E2/P2 Intern Program has recommended savings of more than 214 million gallons of water; 4,100 tons of waste; 35 million kilowatt hours for a total savings of more than \$5 million per year" (The Pollution Prevention Institute Intern Program Case Summaries). Throughout the E2/P2 Intern program, leading to water consumption, waste generation, and energy usage. The \$5 million in annual savings

achieved by this program shows that investing in green chemistry and pollution prevention is not only beneficial for the environment but also economically advantageous, which directly supports the claim that preventing pollution is more cost-effective than cleaning up environmental damage.

3 Catalysis and Energy Efficiency

Implementing catalytic processes for green chemistry may involve upfront expenses, but catalysts increase reaction efficiency, reduce waste, and minimize the need for hazardous reagents. An example would be:

"The U.S. chemical manufacturing sector can contribute to a cleaner future by developing low thermal budget process heating solutions, improving advanced reactions, catalysts, and reactor systems to reduce carbon emissions, and using hydrogen, biomass, or waste as fuels and feedstocks for manufacturing" ("DOE Industrial Decarbonization Roadmap").

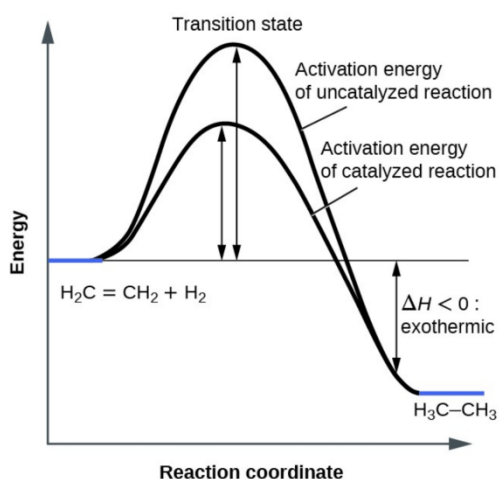


Figure 2: Energy Savings Through Catalytic Processes
(Source: "Catalysis | Chemistry," Lumenlearning)

It highlights the role of the chemical manufacturing sector in sustainability and the development process. It also reflects the green chemistry principle of reducing energy consumption. Those efforts will align with the goal of reducing carbon emissions and promoting eco-friendly chemical manufacturing productions.

Green chemistry also promotes energy efficiency by optimizing energy consumption in chemical processes, which prevents environmental degradation, yielding substantial economic benefits. The pursuit of green chemistry fuels continuous innovation, driving technological advancements that enhance sustainability across multiple industries. "A sustainable and efficient strategy to selectively cleave the specific sp³C–sp³N bond of a thermoset melamine–formaldehyde foam, by which valuable melamine of 99.5% purity was obtained with a yield of 95.3%" (Yang et al.). It highlights a special process that efficiently breaks down melamine–formaldehyde foam. The method is highly aligned with green chemistry, especially with the principle of energy efficiency. It has maximally reduced waste, the use of energy, and optimized the chemical process, which promotes sustainability and cost-efficiency.

Research in peptide manufacturing illustrates how process optimization can significantly reduce the environmental impact. According to Shah, a researcher in Nanjing Tech University, China has claimed that traditional peptide synthesis usually generates a lot of waste and relies on organic solvents causing high product mass intensity. Shah also explains that "A large volume of organic solvents is

generally utilized in SPPS, including those applied in the amino acid coupling, resin rinsing, peptide cleavage/global deprotection, and workup" (Shah). According to the research, one of the main evident manufacturing issues is the waste generated from the production of peptides. At this point, green chemistry has not yet been applied. It indicates the significance of the need for green chemistry. However, after applying green chemistry:

"The target peptide Z could be readily obtained by treating the peptidyl resin with a diluted acid solution, that is, 10% TFA/TFT (trifluorotoluene), and precipitating the solid product in a radically reduced volume of anti-solvent. The MP-SPPS process achieves a 5.3-fold increase in peptide Z manufacturing and complies with the philosophy of green chemistry" (Shah).

This data indicates a 5.3-fold increase in peptide Z manufacturing, which is very significant. This advancement demonstrates how integrating sustainable practices into chemical manufacturing can enhance productivity while minimizing environmental harm. It is a good showcase for applications of green chemistry.

4 Safer Chemical Design and Renewable Resources

4.1 Designing for Safety and Degradation

Green chemistry differs significantly from traditional methods by prioritizing the design of safer chemicals, focusing on the conservation of energy and reduction of carbon emissions, ultimately fostering a safer future for both people and the planet. Unlike traditional chemical processes, green chemistry emphasizes that the safer design of chemicals is important. Green chemistry focuses on the reduction of carbon emissions and energy savings.

Green chemistry has a very strong influence in the area of developing sustainable materials. The opposite of green chemistry is petroleum-based plastics. "The way plastics are currently produced, they contribute to around 3.8% of global GHG (Greenhouse gases) emissions" (Adin et al.). This is research done by the U.S. Department of Energy. The quote highlights the significant environmental impact of plastic production, which takes up to 3.8% of global greenhouse gas emissions. Showing that plenty of fields still rely heavily on plastic, such as fossil fuels, manufacturing, transportation, and disposal. This is a problem that

scientists need to fix.

It is important to develop sustainable alternatives. Scientists found out that biobased plastics can help the European Union (EU) to reduce greenhouse gas emissions and meet its zero-net target by 2030 (Bioplastics Facts and Figures). Unlike traditional plastics, bio-based plastics come from renewable sources such as sugar cane or corn. It could lead to a more sustainable environment. "Studies indicate that biobased plastics can emit up to 80% less CO₂ over their life cycle compared to petroleum-based plastics" (Zuiderveen et al.). Even though biobased plastics are a good way to solve the problems caused by petroleum-based plastics, the success still relies on the exchange of management improvement, sustainable sourcing, and widespread adoption.

The principle of Design for Degradation could break down the final product into non-toxic, environmentally friendly products when a traditional chemical process could produce a strong toxic product. "Green chemistry differs significantly from traditional methods by prioritizing the design of safer chemicals, focusing on energy conservation, and reducing carbon emissions, ultimately fostering a safer future for both people and the planet" (US EPA, "Basics of Green Chemistry"). A great example of design for degradation would be PLA:

"PLA could break down within 90 days into non-toxic byproducts. It could be seen as a great replacement of traditional plastics. The global PLA market was valued at USD 1.5 billion in 2023 and is projected to reach USD 3.3 billion by 2028, growing at a compound annual growth rate (CAGR) of 17.1% from 2023 to 2028" ("7 Leading Polylactic Acid Manufacturers").

This quote talks about a new material called Polylactic Acid. The application of polylactic acid could have saved the environment by having a faster degradation rate, which helped save the environment. This is another showcase of the principle of Design for Degradation, showing that using green chemistry is better than traditional chemical methods.

4.2 Reducing Reliance on Fossil Fuels

Green chemistry encourages the shift toward renewable resources such as plant-based materials, reducing dependency on fossil fuels and fostering a more sustainable chemical industry. For example: "In 2020, hazardous waste from auxiliaries accounted for over 400 million

tons globally, highlighting the environmental impact of traditional chemical processes" (Mironescu et al.). This has shown the harm of traditional chemical methods to the environment. Green chemistry could solve this problem by reducing the reliance on harmful auxiliaries. By prioritizing sustainable practices, green chemistry could not only decrease industrial pollution, but also decrease the potential cost. This could help create a more effective method in chemical manufacturing.

Using renewable feedstocks, green chemistry encourages a sustainable, plant-based system to replace fossil fuels and their derived materials. One of the findings of the High Level Group on the Competitiveness of the European Chemicals Industry was that whilst the chemical industry will remain predominantly reliant on petrochemical-based feedstock in the next decades, there is definitely scope for an increased use of renewables as feedstock in the chemical industry. "Currently, renewable feedstock makes up about 7% of total chemical feedstock use. By 2020, the share of bio-based chemicals could reach – subject to the removal of various barriers – a level of 20% of all chemical products (in percentage of sales)" (Green Feedstock for the Chemical Industry). As the research indicates, there is a strong potential for renewable feedstocks. Those potentials could turn into an evolution of chemicals. Even though the factories still strongly rely on oil and traditional chemical processes, there is a huge potential and space for development for renewable alternatives. The projected rise from 7% to 20% in renewable feedstocks indicates that there is an industry shift toward greener processes. This kind of transition could not only reduce the reliance on some limited sources but also reduce the impact of traditional chemical processes, making green chemistry a more practical and sustainable method compared to normal chemical methods. A great example would be the number provided by The U.S. Department of Agriculture's 2023 report, which highlights that "biorefineries currently produce an estimated 150 million gallons of raw materials per year, which are used to manufacture biobased products" (Golden et al.). The number provided indicates the strong reliance on finite resources. There must be a shift in chemical industrial methods. Green chemistry could be a great fit.

4.3 Real-Time Analysis for Pollution Prevention

Another principle of green chemistry, which could address

environmental pollutants and toxicant risks and prevent industrial accidents, is Real-time analysis for Pollution Prevention. Real-time analysis for Pollution Prevention is an analytical method that controls an ongoing chemical reaction during the production process. The process of analysis could be in-line, on-line, or at-line in a production process. This type of analysis could detect some minor or major changes such as a change of pH or temperature to define the toxicity of the solution or catalysts (Anastas and Warner). They have significantly damaged the environment. Dr. Jaishankar points out that the increase in the use of heavy metals has resulted in an imminent surge of metallic substances in both the terrestrial environment and the aquatic environment (Jaishankar et al.). Those metallic substances deeply affect the environment as well as our lives.

A quote mentioned in a research called Heavy Metal Pollution in the Environment and Their Toxicological Effects on Humans:

"Boehringer Ingelheim developed a three-step asymmetric synthesis route for an intermediate compound, which improved the yield nearly five-fold from 10% to 47%, reduced organic solvent usage by 99%, and decreased water usage by 76%" (Arnum).

This quote from Arnum has given an example of the successful application of real time analysis. During the chemical process, the accuracy of real-time control has increased the efficiency sustainability. The yield has not only increased from 10% to 47%, but also decreased water usage by 76% and reduced organic solvent usage by 99%. This is an important step to decrease the impact to the environment. This example has shown that the principle of green chemistry can bring up long term benefits especially environmental benefits. Even though a tremendous amount of investment is required upfront, the benefit is more valuable.

5 Conclusion

Green chemistry represents the shift of the way that chemical manufacturing is designed. Green chemistry is not repair after damage occurs. Green chemistry emphasizes that by using a safer chemical design, improving energy efficiency and using sustainable materials to prevent pollution. So far, the advance in this research paper has

indicated that the prevention is not only responsible to the environment but also economically advantageous.

The pollution prevention programs and industrial cases have suggested that reducing waste and improving efficiency could bring out significant economic savings while lowering the impact towards the environment. The innovations in catalytic processes, renewable materials and sustainable feedstocks could illustrate how green chemistry changed and revolutionized the traditional chemical industrial process. Those methods could reduce the impact and reliance towards dangerous chemicals and fossil fuel, as well as improving the efficiency of production.

Even though green chemistry might require high initial cost, its long term benefits including reducing damage towards the environment, lowering the operational costs and improving its sustainability has far beyond those early investments. The development of green chemistry could build a better world for humans to live in.

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