# Meeting the challenges to sustainability through green chemistry

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## Background

During the course of the past year, there has been a heightened degree of focus on sustainability due in some part to the World Summit on Sustainable Development in Johannesburg, South Africa. The discussions in preparation for that meeting as well as the statements and declarations that resulted provide ample evidence of a growing consensus that the world faces serious challenges to its sustainability. Sustainability for the purposes of this discussion will be defined as according to the Brundtland Commission, ‘The ability to meet the needs of the current generation while preserving the ability of future generations to meet their needs.’ A simpler way of expressing this idea may be, ‘Preserving the things you cannot live without and preserving them forever.’

Any listing of the major challenges facing the sustainability of Earth will generate debate and refinement. However, most may agree that among the most pressing issues facing the planet would be the following:

- Population growth
- Energy
- Food supply
- Resource depletion
- Global climate change
- Water
- Toxics generation and dispersion

It would be reasonable to argue that the above list, both individually and collectively, constitute the major challenges to sustainability. As such, these issues must constitute our highest priorities since the failure to meet these challenges will mean that the human society may not be around to meet any others. What role does green chemistry have to play in meeting these challenges and the ultimate goal of sustainability? Green chemistry fulfills a fundamental and crosscutting role that is essential to the critical pathway toward sustainability. Simply stated, it is difficult to imagine a way to address the challenges of sustainability without engaging in green chemistry.

To understand some of the challenges our society must confront, it is useful to recognize that society has previously been on an unsustainable trajectory. In fact, one hundred years ago there were predictions that the volume of waste produced by the increasing number of horses in the New York City would virtually bury the entire population. This future was not avoided by placing a legal ban on horses. Rather, it was through the engagement of science and technology and the invention of alternative personal transportation means that the trajectory was changed.

Furthermore, meeting the challenges requires a planning perspective of the century or longer timeframe rather than merely focusing on years or decades. For example, a resource planner in the year 1900 would want to ensure that there was an ample supply of whale oil in the year 2000 for lighting, wood for fuel, rock salt for refrigeration and horses for personal transportation. By relying on such resources, society was on an arguably unsustainable trajectory. Again, it was through the engagement of science and technology that shifted society toward greater growth and sustainability. Similarly, in order to shift society from the current projected unsustainable trajectory, it is once again necessary to engage science and technology to achieve the goal of sustainability with green chemistry as part of the foundation.

## Discussion

In using green chemistry as the approach toward meeting the goals of sustainability, there is embedded the recognition that all that is available in the universe is energy and matter. Since the hazards we confront are based in the physical/chemical properties of the molecules we make, it is the manipulation of these very physical/chemical properties that is the most powerful method we have to confront these hazards. Through the design of matter at the molecular level, we can deal with fundamental problems such as toxicity, renewability and global impact. Even our energy concerns are based on the matter (materials) that are used to generate, store and transport our energy supply.

Green chemistry shifts the approach to addressing issues, such as environmental problems, from the *circumstantial* to the *intrinsic*. Virtually every significant approach to dealing with environmental issues has tried to change the circumstances or the conditions of the problem. By changing conditions, we attempt to ensure that hazardous chemicals, for instance, cannot escape in high concentrations to the environment or that these chemicals are treated before disposal. The difficulty with simply attempting to change the conditions of a given process is the additional expense, often in the form of engineering controls that are simply a cost drain. These attempts at trying to make unsustainable products, processes and systems a little less bad through changing the conditions can be costly. In addition, if

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conditions change such as in the case of accidents or malice, the consequences are at a maximum because the hazard remains intact.

Typically, regulations specify maximum limits and best available technologies to control conditions. Trends in regulation (Fig. 1) and in the costs of compliance with these regulations and other environmental expenditures by industry (Fig. 2) over time illustrate the economic burden of this approach even in light of the benefits it has brought about. This methodology should stand in contrast to the approach that green chemistry proposes, namely, to deal with the issues at the intrinsic level.

Green chemistry addresses hazards, whether physical (flammability, explosivity), toxicological (carcinogenicity, endocrine disruption), or global (ozone depletion, climate change) as an inherent property of a molecule. Therefore the hazard can be addressed through appropriate design of the structure and its associated physical/chemical properties at the molecular level. This approach has the advantage of not requiring expenditures of non-productive capital such as is the case in waste treatment plants. Again, by minimizing the inherent nature of the hazard you reduce the potential for catastrophic events through accident or breakdown.

## Population

The first of the challenges to sustainability, population, drives many other challenges as well. While it took all of human history until 1930 to reach a population of 2 billion (Fig. 3) it has taken only 70 years to triple that number to 6 billion. If United Nations population projections are accurate, we will have another billion people on the planet in the next 10 years with China adding the equivalent of the current population of the United States. It is important to understand where this population growth is taking place. As seen in Fig. 4, while population growth in the most developed economies with the highest standard of living is virtually stagnant, the population growth in developing nations with the lowest standard of living is increasing at a significant rate.

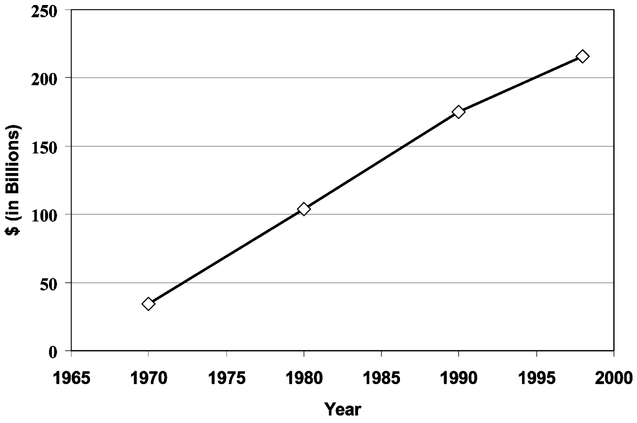

*Fig. 2 Environmental expenditures in billions of dollars from 1970–1998. Source.*[25]

Drawing from the empirical data on this very complex issue, it is difficult to ignore the correlation between increased quality of life and sustainable population growth. Employing a strategy of achieving more sustainable population growth through an increased quality of life in developing nations is one that is compelling but not without drawback. The drawback is reflected in the historical trend that increased quality of life was often associated with increase resource utilization and degradation of the environment (Fig. 5). Therefore, one needs to recognize that any approach to population stabilization involving an increase in quality of life must be inextricably linked to doing so in a way that minimizes the impact on human health and the environment (Fig. 6). Green chemistry possesses the framework, techniques and methodologies to achieve this goal as seen in examples of

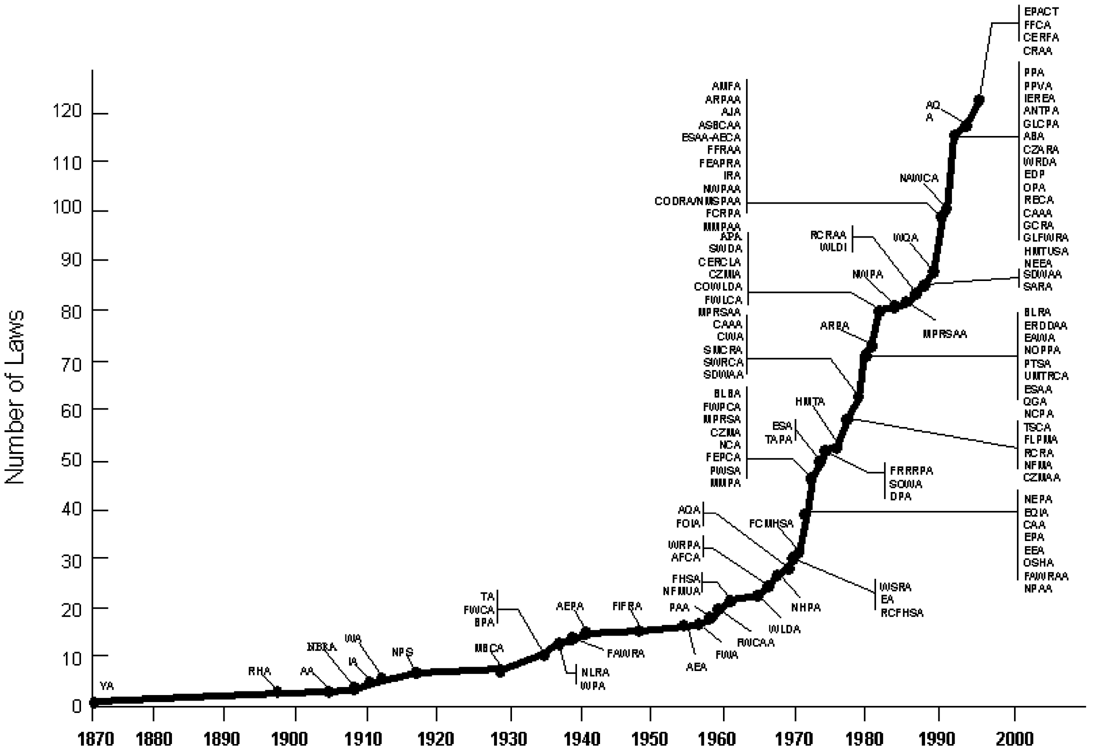

*Fig. 1 Expansion of environmental regulation in the United States from 1970 to present. Source:*[24]

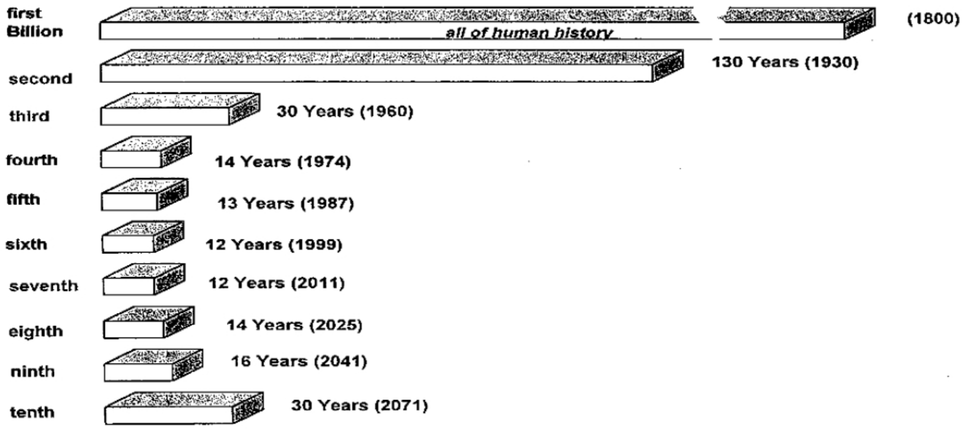

***Fig. 3** Number of years required to add each billion to the world population. Source.*[26]

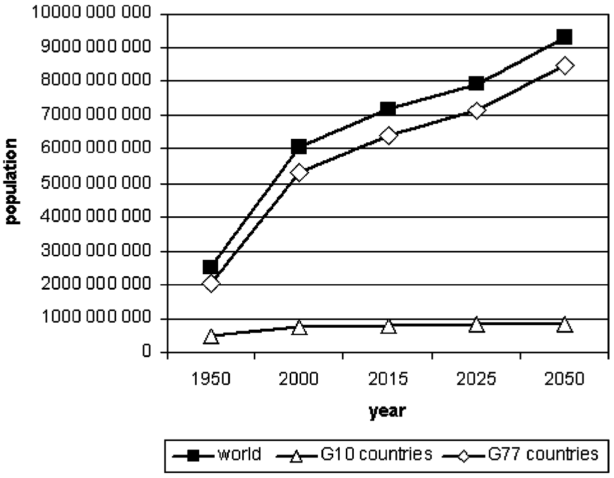

***Fig. 4** Projected population growth in industrialized (G10) and developing (G77) nations based. 2000 projections, medium variant. Source.*[27]

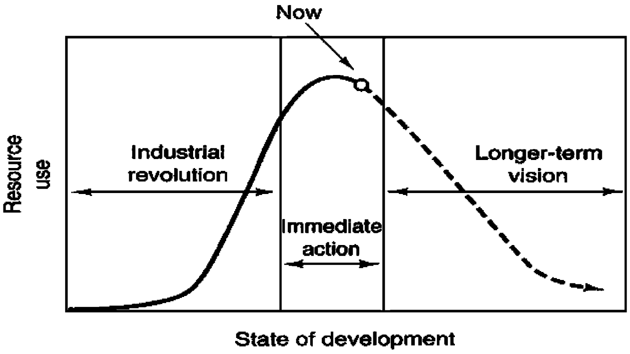

***Fig. 5** Schematic of resource use versus state of development. Source.*[28]

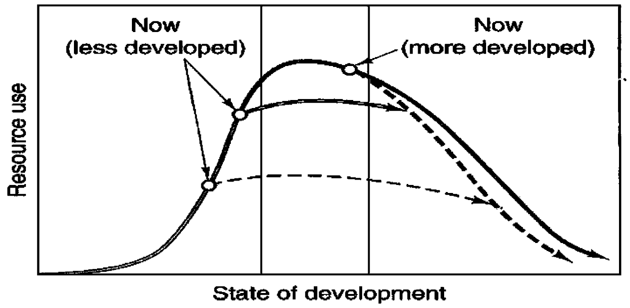

***Fig. 6** Schematic of alternative leap frog technology for development. Source.*[28]

the engagement of green chemistry on the other challenges listed below.

## Energy

Currently, the energy supply of the world is largely based on the combustion of carbon. The extraction and collection of carbon through mining, drilling, processing, etc. has well documented environmental consequences. The production of carbon dioxide and other gases has been cited as contributing to global warming both by the International Panel on Climate Change (IPCC), as well as the National Academy of Sciences in the U.S.[1,2] While the exact impacts of the generation of associated toxics during the production of fossil fuels and the rate at which this finite resource is being depleted will perhaps always be the topic of varying analyses, these are also areas of environmental concern.

Projections of energy needs suggest that energy demands will continue to increase in order to support development and a growing population (Fig. 7). The question is 'What type of energy future will supply these energy needs?'. Current projections (Fig. 8) would suggest a continued domination by fossil fuels. Green chemistry, however, is engaged in addressing energy needs through the development of more sustainable energy technologies.

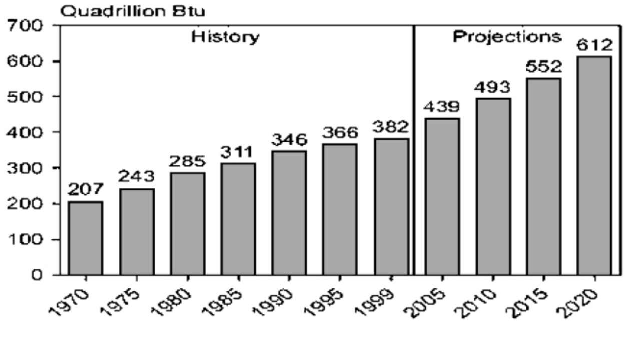

***Fig. 7** World energy consumption from 1970 to present and projected to 2020 in quadrillion btu. Source.*[29,30]

The principles of green chemistry[3] are being employed in the development of the hydrogen economy and fuel cells. The sustainable sources of hydrogen generation in an economically sustainable manner are an area of active research both in green chemistry and green engineering.[4,5] The design and development of photovoltaics and solar energy devices that are both economically viable and also ensure a positive energy balance through their manufacture and use is being pursued.[6] Materials

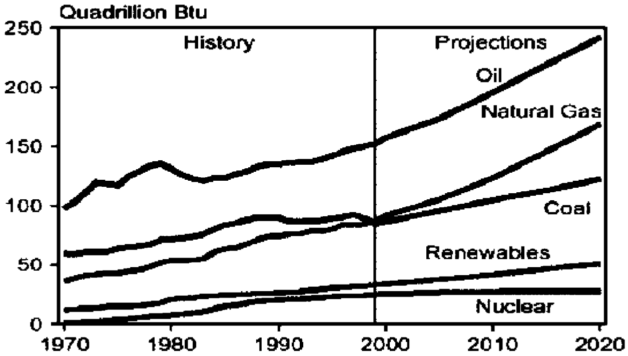

*Fig. 8 World energy consumption by fuel type from 1970 to present and projected to 2020. Source.*[29,30]

that are needed to make wind and geothermal energy systems possible are being developed through green chemistry research. The energy future will need to be shifted to a more sustainable balance and green chemistry is essential in making that shift happen.

## Food supply

Currently, the world produces enough food to feed its population. While regional starvation exists for reasons ranging from distribution to economics to politics, the miracle of the efficiency of modern agriculture is undeniable (Fig. 9).

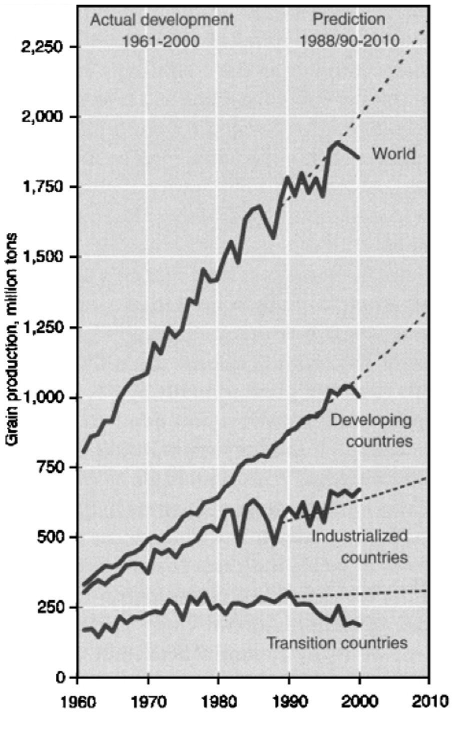

*Fig. 9 Actual grain production in million tons from 1961 to 2000 and projected grain production from 2000 to 2010. Source*[31,32]

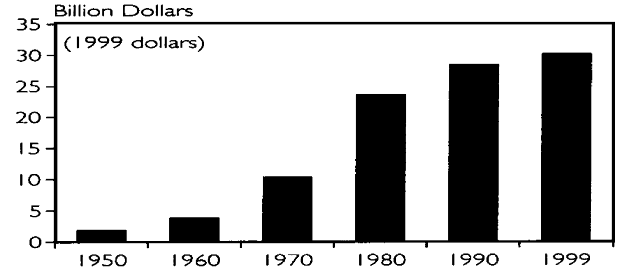

*Fig. 10 Global pesticide sales from 1950–1999 in billion 1999 dollars. Source.*[33]

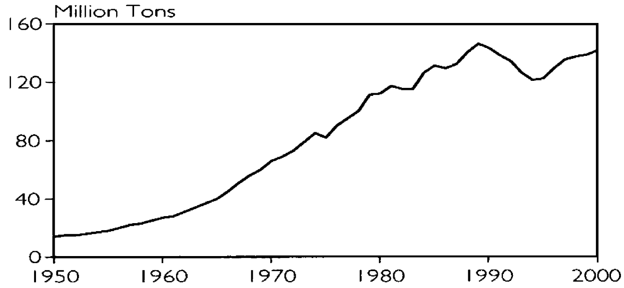

*Fig. 11 Global fertilizer use in million tons from 1950–2000. Source.*[33]

However, the historical methods used to achieve this efficiency have not generally been sustainable. The use of pesticides (Fig. 10) and fertilizers (Fig. 11) has grown substantially with the environmental consequences of agricultural run-off well documented. Green chemistry has witnessed advances in the development of new and more sustainable pesticides that are both targeted very specifically to only pest organisms and do not persist in the environment.[7–10] In addition, fertilizers and fertilizers adjuvants are significantly decreasing the amount of material that needs to be applied to the land in order to achieve the same beneficial activity.[11] Continued development of compounds to improve agricultural efficiency by green chemistry will be one essential component of achieving sustainable agricultural systems to meet the needs of the additional billions of people expected to populate the planet.

## Global climate change

While projections of climate change show a global warming trend, most models show that some places may get warmer while some get cooler; some places will get drier while some get wetter. Exactly where and at exactly what rate these projections will be manifested is still the subject of reasonable debate. What is certain, however, is that approaches to minimize the generation and release of greenhouse gases to the atmosphere will require new science and technology that deals with the issue in an economically and environmentally sustainable manner. There is current research on simple sequestration technologies for carbon dioxide. While there will be attempts to make this as least costly as possible, these technologies will still be a **cost** rather than **value adding.** Green chemistry research is seeking to design and develop methods that will utilize carbon dioxide in fixative ways that are value adding, such as in polymer materials[12] and on potentially much larger scales such as building materials and concrete.[13] Changing the equation from carbon dioxide as a waste to using it as a value added feedstock would be an essential pathway to dealing with the goal of controlling carbon dioxide in a manner that is both economically and environmentally sustainable.

## Resource depletion

The use of limited finite resources becomes and increasingly important issue as population increases. It has been stated that in order for the current population of the Earth to live at the same quality of life as the industrialized nations, it would require the resources of four ‘Earth equivalents’.[14] Other analyses state that sustainability will require a least a four-fold (others say ten-fold) increase in material efficiency, that is getting the same function for one-quarter or one tenth the material.

Renewable resource utilization is a central tenet of green chemistry and a very active area of engagement. Use of biomass as feedstock is being developed in everything from polymers,[15] materials[16] and fuels.[17] The use of nanoscience is beginning to be pursued to achieve material efficiency through green chemistry that will have potential applications from computing to energy storage and others not yet imagined to meet the goal of sustainability.[18] Non-conventional biomass such as seafood by-products, *e.g.*, chitin, continue to be developed into materials like chitosan.[19] However, an overarching theme may be that green chemistry strives to turn materials and energy sources that may have once been viewed as waste into value added renewable materials.

## Water

Water, perhaps the molecule most associated with life on Earth, is also one of the greatest challenges to sustainability in the 21st century. Thirty percent of the world′s population will face water shortages by the year 2050, according to the United Nations Environment Program (UNEP).[20] The water crisis is so severe that, according to UNEP:

- Every eight seconds, a child dies from a water-related disease
- 50 percent of people in developing countries suffer from one or more water related diseases
- 80 percent of the diseases in the developing world are caused by contaminated/polluted water;
- 50 percent of people on Earth lack adequate sanitation

In many countries, water shortages stem from inefficient use, degradation of the available water by pollution and the unsustainable use of underground water in aquifers. Green chemistry is improving water supply and water quality through the prevention of contamination and more environmentally benign treatment methodologies. In addition to finding alternatives to unsustainable water use in applications like manufacturing, Green chemistry is also being engaged to find more sustainable ways to purify drinking water. Through the use of totally chlorine-free disinfection agents, water can both be pure and also not contribute to the generation of toxic and bioaccumulating substances.[21]

## Toxics in the environment

The generation and release of toxic substances to the environment remains a global issue. In the U.S. alone, over 7 billion pounds were released directly to the air, water and land in the most recent TRI reporting.[22] Persistent, bioaccumulating and endocrine disrupting chemicals are of serious concern in both the industrialized and developing world. One of the greatest strengths of green chemistry is its focus on the molecular basis of toxicity. Through an understanding of the mechanisms of action of toxicity both in the body and within ecosystems, green chemistry engages to design molecular structures that are inherently either incapable of manifesting a particular toxic endpoint, or at a minimum, greatly disfavoring these toxic mechanisms.[23] These principles and techniques have been applied to substances ranging from dyes to pesticides to plastics to pharmaceuticals.

There are those that often quote the 16th century physician and patriarch of toxicology, Paracelsus in his admonition that ‘Everything is toxic, it is simply a matter of the dose.’ This obvious citation is taken a reminder that we can never say that something possesses **absolutely no** toxicity. It is important while recognizing the immense complexity of toxicological mechanisms, not to overstate this trivial but true fact. While we may never be able to reach perfection, it is an extremely worthwhile goal to move from extremely potent toxic substances to those that are many orders of magnitude less hazardous. Stated another way:

### *Ode to Paracelsus*

*It’s important to heed Paracelsus*
*‘All’s toxic, just depends on the dose’*
*And to condemn those who tell us,*
*it means hazard can’t be controlled.*

*While all things may be able to harm us.*
*It does not mean that all are the same.*
*to scientifically disarm us*
*would do us all great shame.*

*The substances we need to design*
*would make Paracelsus proud.*
*Then we can drink 10 liters of ‘benign’*
*And perhaps we may only drown.*

## Conclusion

The challenges of sustainability are among the most complex and daunting ever faced by society. It may well be that only by working at the most fundamental level, the molecular level, that we can address these complex, global issues in an environmentally and economically sustainable manner. Green chemistry is engaged and needs to be increasingly engaged in facing these challenges by addressing the intrinsic nature of our materials and energy to make them more sustainable. No one is arguing that green chemistry alone will lead to sustainability. However, with green chemistry as an essential element, the path toward sustainability can be traversed, without the engagement of green chemistry, the existence of a path is not clear.

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