E] Green chemistry in sustainable development:

Sustainability:

In the 1987 book *Our Common Future*, the World Commission on Environment and Development recognised that continued industrial and societal development was necessary if a growing planetary population was to be fed, housed and provided with a satisfactory quality of life. It also recognised that it was necessary to make such development sustainable over time, to 'meet the needs of the present without compromising the ability of future generations to meet their own needs'. Twelve years later, in *Our Common Journey*, the Board on Sustainable Development of the US National Research Council reinforced and expanded this basic concept. The Earth Summit was held in Rio de Janeiro in 1992 to reconcile the worldwide economic development with environmental protection where Agenda-21 was adopted that aimed to reduce wasteful materials, fight against poverty, protect the environment and promote sustainable agricultural practices. In 2002, The World Summit was organized in Johannesburg to review the progress in this regard since The Earth summit.

As a result of these initiatives, 'sustainable development' has become a common phrase, and many corporations advertise their operations as 'sustainable'. The use of the word is seldom defined in this context, but it is clear that two central implications are:

1. Using natural resources at rates that do not unacceptably draw down supplies over the long term.
2. Generating and dissipating residues at rates no higher than can be assimilated readily by the natural environment.

Accordingly, one cannot evaluate the environmental performance of a facility solely on the basis of such classical green chemistry metrics as the rate of reduction in the volume or toxicity of disposable byproducts. In addition, it is necessary to evaluate one's processes and operations in terms of long time spans, broad spatial scales and complex interactions with natural systems, and taking actions that are indicated by such an evaluation whether they are regulated or not.

This perspective of sustainable development demands new ways of measuring and understanding the industry–environment relationship. It is the core of our thinking in the evaluation of an individual facility, an entire industrial sector or the entire technology of the planet. If a facility, a corporation or a sector is to be truly 'sustainable', it must see its activities not from a parochial viewpoint but from one that encompasses the long-term requirements of 'Spaceship Earth'.

To completely understand and quantify the greenness and sustainability of products and processes, simply mass-based metrices such as atom economy, or E-factor is not sufficient. These metrices need to be augmented by Life Cycle Assessment (LCA) which measures the environmental impact of a product through every phase of its life.

LCA involves consideration of various factors such as:

1. Which raw materials were involved in the production process, and where do they come from? What about soil, seeds, and fertilizer?
2. How do the goods get produced? What about heating, water, and ventilation?
3. How did the goods get transported? Via truck, rail, or airplane?

Through consideration of these and several other factors, LCA attempts to draw an environmental profile of a product and the process involved in its production so that the environmental impact of those can be quantified.

Generally, the product life cycle consists of five phases:

1. Raw Material Extraction, 2. Manufacturing & Processing, 3. Transportation, 4. Usage & Retail, 5. Waste Disposal.

Different life cycle models: Based on the stages we are interested in or have data available on, we can choose to leave in or take out phases. There are usually four product life cycle models we can choose for our LCA.

1. Cradle-to-grave:

When we analyze a product's impact along the 5 product lifecycle steps outlined above – this is called cradle-to-grave. The cradle is the inception of the product with the sourcing of the raw materials, the grave being the disposal of the product. Transportation is mentioned as step 3, but can, in reality, occur in between all steps.

2. Cradle-to-gate:

Cradle-to-gate only assesses a product until it leaves the factory gates before it is transported to the consumer. This means cutting out the use and disposal phase. Cradle-to-gate analysis can significantly reduce the complexity of an LCA and thus create insights faster, especially about internal processes. Cradle-to-gate assessments were common in environmental product declarations (EPD), but revised doctrine now mandates a cradle-to-grave approach. (Environmental Product Declarations are standardized certifications of a life cycle assessment, used mostly to verify impact data from business to business).

3. Cradle-to-cradle:

Cradle-to-cradle is a concept often referred to within the Circular Economy. It is a variation of cradle-to-grave, exchanging the waste stage with a recycling process that makes it reusable for another product, essentially "closing the loop". This is why it is also referred to as closed-loop recycling.

4. Gate-to-gate:

Gate-to-gate is sometimes used in product life cycles with many value-adding processes in the middle. To reduce complexity in the assessment, only one value-added process in the production chain is assessed. These partial assessments can later be linked together to complete a larger level Life Cycle Assessment.

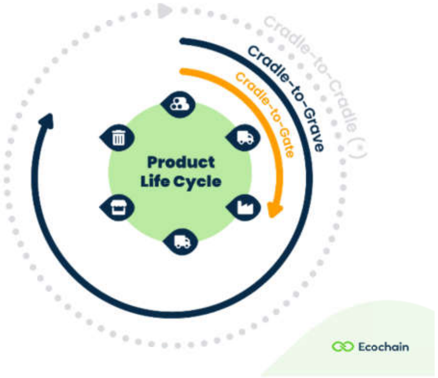


Image source: https://ecochain.com/blog/life-cycle-assessment-lca-guide/

Let us take a closer look at the different stages of LCA. LCA has four stages, namely:

1. Definition of Goal and Scope: a) What will we be assessing, and why? B) How extensively will we be assessing? c) Which guidelines and methods will we follow?

2. The Life Cycle Inventory Analysis (LCI): This is essentially the data collection phase of our LCA. It looks at the environmental inputs and outputs of our product or service. The goal is to quantify the environmental inputs and outputs – this means we measure everything that flows in and out of the system we defined in Stage 1. What could these inputs and outputs be? Raw materials or resources, different types of energy, water, emissions to air, land, or water by substance, etc.

3. Life Cycle Impact Assessment (LCIA): Until now, we defined what we want to measure and collect in Stage 1. Then we collected and structured the data in Stage 2. In Stage 3, we evaluate how significant the impacts are. There are three key tasks in this step, which are nowadays taken over by LCA software.

Task 1: Selection of indicators and models: Common indicators are: Human toxicity, Global Warming Potential (carbon footprint), Ecotoxicity, Acidification, Eutrophication.

Some impact categories are measured in equivalents, often seen as a lowercase e or eq, for example, CO_2-*e* for CO_2-equivalent. This is because several emissions contribute to the same impact category. For example, climate change or global warming potential (GWP) is measured in CO_2-equivalents. This doesn’t mean only CO_2 contributes to global warming, because, for example, also methane and nitrous oxide play a role there. But to consolidate all gases into one indicator, all other gases are transposed into CO_2 equivalents.

Task-2: Classification: In this step of our LCIA, we (our software) assign our LCI to our defined impact categories. For example, our LCA software classifies CO_2, CH_4, and N_2O as having climate impacts.

Task 3: Impact Measurement: In the last step of our impact assessment, we (our software) finally calculate all our equivalents. We sum them up in overall impact category totals.

4. Interpretation of our Life Cycle Assessment: With all the data in place, we make the most reliable conclusions and recommendations. This has to be done cautiously and the results have to be put in context to analyze the overall picture. What we want to interpret is also defined in the ISO norms defining the Life Cycle Assessment. According to ISO 14044:2006, this is what the interpretation of a Life Cycle Assessment should include:

a) Identifying significant issues based on our LCI and LCIA phase;
b) Evaluating the study itself, how complete it is, if it’s done sensitively and consistently;
c) Conclusions, limitations, and recommendations.

Which conclusions can we draw from our assessment?

We started the entire task by defining our goals upfront. Now, after we gained a lot of insights into our product or service, we can draw conclusions from it, such as:

a) How high are the emissions of the product or service?
b) How does it compare to other products in our portfolio?
c) What are the biggest leverages to reduce the impact of our product?
d) Can we be more efficient in manufacturing it?

Sustainability and Green chemistry:

What is it that we would like to sustain? From the perspective of green chemists, there appear to be four items of interest in this regard:

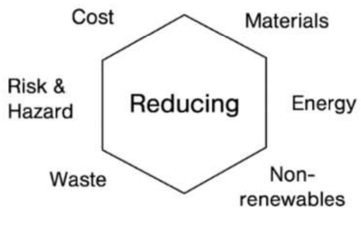
1. Chemical feedstocks: Experience and theory in green chemistry indicate that there are many potential paths from starting materials to products, and, for many products, alternative potential starting materials. In the case of petrochemicals, the obvious potential alternatives are feedstocks based on biotechnology and derived from agricultural approaches. This means that development of biotechnological feedstocks needs to be brought on line rapidly, because they will probably need to overtake feedstocks based on petroleum within about 30–40 years and become the dominant feedstock in about 60–70 years.

2. Energy for feedstock processing: The use of fossil fuels is ultimately unsustainable because of supply considerations. It appears possible as well that use of any energy-producing source that involves combustion and CO2 generation may be constrained by global warming concerns. Thus, truly sustainable energy resources can be regarded as fissile materials, hydropower, solar power, wind power, geothermal power and ocean power, whereas unsustainable sources are petroleum, natural gas, coal and biomass. A facility moving towards sustainability is therefore one that is beginning a transition from unsustainable sources of energy to sustainable ones.

3. Water for feedstock processing: The quantification of the water supply in the area where the synthetic facility is located, estimation of requirement of the separate sectors including residents of that area (with minimum water requirement per capita) and then allotment of the water resource to those sectors: residential area, agriculture, industry, commercial, etc. Ideally, such an allocation would be based on minimum need for specific purposes.

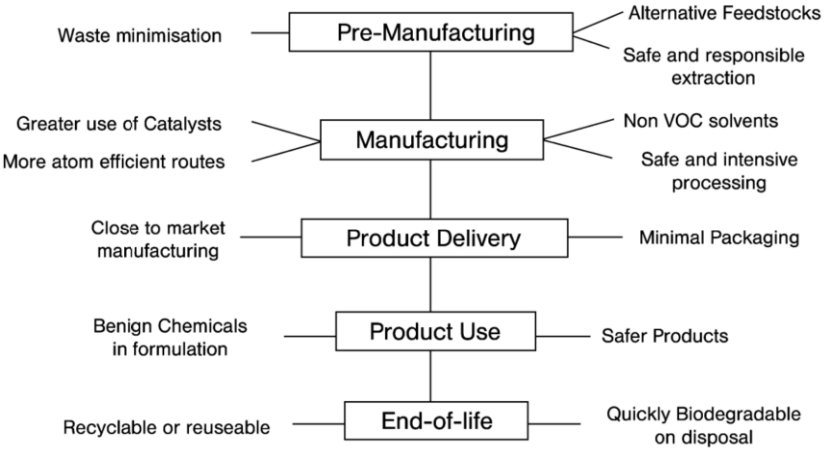
4. Environment resilience: The final element of the sustainability of a facility refers to the capability of the ecosystems with which it is in contact to receive any dissipated residues without suffering significant degradation. This criterion has proved essentially impossible to quantify. For some inorganic species, such as the sulfate ion, the concept of ‘critical loads’ has provided general guidelines. For most emittants, however, the potential environmental implications have proven too diverse and too subtle to yield a simple quantitation. The only possible approach to minimize environmental impact is to adopt ‘zero discharge’ as a target. Although probably unattainable in practice, such a goal has the potential to inspire markedly improved environmental performance. An appropriate approach to the preservation of environmental resilience thus is to reduce gradually all emissions to the environment from industrial processes to zero.

Green Chemistry can be considered as a series of reductions. These reductions lead to the goal of triple bottom-line benefits of economic, environmental, and social improvements. Costs are saved by reducing waste (which is becoming increasingly expensive to dispose of, especially when hazardous) and energy use (likely to represent a larger proportion of process costs in the future) as well as making processes more efficient by reducing materials consumption. These reductions also lead to environmental benefit in terms of both feedstock consumption and end-of-life disposal. Furthermore, an increasing use of renewable resources will render the manufacturing industry more sustainable. The reduction in hazardous incidents and the handling of dangerous substances provides additional social benefit – not only to plant operators but also to local communities and through to the users of chemical-related products.



Book Consulted: An Insight into green Chemistry by Chandrakanta Bandopadhyay; New Trends in GREEN CHEMISTRY by V. K. Ahluwalia and M. Kidwai; A Textbook of Green Chemistry by S.P. Dey and N. Sepay

It is particularly important to seek to apply Green Chemistry throughout the lifecycle of a chemical product:



Taken from: Green Chemistry and Environmentally Friendly Technologies – Clark, in Green Separation Processes (2005)

Scientists and technologists need to routinely consider lifecycles when planning new synthetic routes, when changing feedstocks or process components, and, fundamentally, when designing new products. Many of the chemical products in common use today were not constructed for end-of-life nor were full supply-chain issues of resource and energy consumption and waste production necessarily considered. The Green Chemistry approach of "*benign by design*" should, when applied at the design stage, help assure the sustainability of new products across their full lifecycle and minimize the number of mistakes we make.

In summary, green chemistry can work towards sustainability by:

1. Increasing use of renewable raw materials instead of non-renewable resources,
2. Preventing the formation of waste than to treat or clean up after it is formed,
3. Designing atom economic processes so that all feedstock can be included into the product.
4. Forming safer products, harmless for humans and environment.
5. Designing environmentally friendly technologies that reduce / eliminate the use of toxic materials – chemicals and solvents.
6. Using non-conventional sources of energy (MW, US etc.) that reduces product cost and save energy and environment.
7. Using safer catalysts.
8. Designing biodegradable products.
9. Designing greener alternatives for existing methods.
10. Designing methods that produce biodegradable waste in case the waste is not recyclable.

Ref:

1. Green Chemistry and Sustainable Development – Graedel, in *Handbook of Green Chemistry and Technology (2002)*.

2. Green Chemistry and Environmentally Friendly Technologies – Clark, in *Green Separation Processes (2005)*.

3. https://ecochain.com/blog/life-cycle-assessment-lca-guide/