There is no doubt that the planet is facing a number of crises: from climate change and weird/dangerous weather patterns to air pollution and ocean plastics not to mention habitat loss due to industrialisation. Is it going to be resolved if we reduce consumption, reuse items, and recycle those we can't both at home and at work?

Dr Ali Green

GREEN CHEMISTRY

A discussion provoked by the Green Chemistry Masterclass by John Warner at IFRA 2021

Surely the virtuous warm feeling I get when re-using a plastic ice cream tub to store batch-cooked spaghetti sauce in the freezer or dutifully put out the fortnightly recycling for the local refuse team to pick up is justified? If enough people were to do the same, won't all these issues of plastic and air pollution along with climate change resolve themselves? Well, the short answer according to John Warner is an emphatic no! It definitely won't make things worse, but (and it's a big BUT) unless green chemistry techniques and strategies are employed across the entire manufacturing processes, things will inevitably be unsustainable. So the big question is what can we, in industry do about this major global problem? Well, just as the genius of Chemistry has created many of the processes and products we know to be problematic, it too can solve many of the problems by rethinking the process of new product development and manufacturing using nature as its template.

Firstly, it's important to understand why the current policies of most governments and industries of 'reduce, reuse and recycle' won't create a stable and sustainable system. John explained this very neatly with an excellent diagram explaining current processes, which I summarise here using a step-by-step process.

1. Natural resources are subjected to extraction processes
2. The extraction processes give us molecules and ingredients which are then synthesised
3. The synthesis gives us materials and components which are then manufactured
4. The manufacturing creates finished products

Now, according to the 're-use' element of standard eco policy, we should try to remain at 4 for as long as possible with a product, repairing if necessary. However, we all know, particularly with one shot plastics this can't always be the case. Plus, every product will eventually be rendered unusable due to the inevitability of entropy*, even my faithful ice cream tubs that have been washed and re-used numerous times. For some products this will be a really long process, whereas for others it may happen after a relatively short time. The adoption of built-in obsolescence or product failure as a manufacturing strategy to ensure more sales has accelerated this unnecessarily in many areas of manufacturing: products are not created to last!

Once entropy occurs, the products have to be broken down into components using mechanical or chemical recycling strategies (nearly all of which use energy) so we are back to stage 3 again. This will form a neat manufacturing and recycling loop for a while until, yet again, the inevitable entropy comes into play meaning recycling is no longer an option, meaning that these damaged components will have to be subjected to molecular reprocessing, returning us to stage 2 once again. Stage 2 can also maintain a stable system for some time for some components but will, like stage 3 and 4 also inevitably fail.

In order to get back to natural resources at the beginning of stage 1, however, we have what can be a lengthy process of degradation. In fact anything that ends up in landfill at the end of stage 4 without being reused or recycled, will also be subject to degradation. It is at this stage that we often see environmental leaching and pollution.

Thus by adopting traditional chemical manufacturing strategies and widely adopted sustainability policies, John bluntly says we are going against nature itself. By moving from 1 to 4 using very clever but unnatural methods to achieve goals we are setting up a pendulum effect rather than a closed loop since nature will always follow the laws of physics (notably entropy) and move from 4 down to 1. This is where green chemistry techniques come in – it is an opportunity to examine what techniques create a sustainable system in nature and mimic that in order to produce exciting new products. The trouble is here that chemists have been taught to break chemical bonds using heat, current or strong solvents (let's face it, this is a challenge and also quite satisfying): new functional groups are added on to artificially created molecules in order to develop a multi-functional, but often inherently unstable molecule, that satisfies all requirements in the brief but naturally wants to split so requires some form of chemical/physical coercion to remain and do its job. Many geniuses of the Chemistry world have created some incredibly complex and clever products and processes that are used worldwide. Now, however, an urgent revision is needed as we fully realise the impact of these brilliant processes on the planet and its natural ecosystems.

* This web page has an excellent definition of entropy that is ideal for those unfamiliar with the concept: - https://heinenhopman.com/en/about-us/blogs/20200625_what-is-entropy-part-1-a-simple-definition/

John believes that education is the key here, going right back to high school chemistry, through university to graduate school, with 12 basic principles of green chemistry taught alongside curriculum staples.

1. **Prevention:** It is better to prevent waste that to treat or clean up waste after it is formed
2. **Atom Economy:** Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product
3. **Less Hazardous Chemical Synthesis:** Whenever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment
4. **Designing Safer Chemicals:** Chemical products should be designed to preserve efficacy of function while reducing toxicity
5. **Safer Solvents and Auxiliaries:** The use of auxiliary substances (solvents, separation agents etc.) should be made unnecessary whenever possible and, when used, innocuous
6. **Design for Energy Efficiency:** Energy requirements should be recognised for their environmental and economic impacts and should be minimised. Synthetic methods should be conducted at an ambient temperature and pressure
7. **Use of Renewable Feedstocks:** A raw material or feedstock should be renewable rather than depleting whenever technically and economically practical.
8. **Reduce Derivatives:** Unnecessary derivatisation (blocking group, protection/deprotection, temporary modification of physical/ chemical processes) should be avoided whenever possible.
9. **Catalysis:** Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation:** Chemical products should be designed so that at the end of their function they don't persist in the environment and instead break down into innocuous degradation products
11. **Real-time Analysis for Pollution Prevention:** Analytical methodologies need to be further developed to allow for real-time in-process monitoring and control prior to the formation of hazardous substances
12. **Inherently Safer Chemistry for Accident Prevention:** Substance and the form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions and fires.

(https://www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html)

These principles are not intended to clip the wings of creative chemists. Rather they should be viewed as a new challenge for chemists to rise to and create or discover some brilliant new molecules that could revolutionise industry for the future. For John, the key is to observe what happens in nature. For many of us, this can most easily be seen in our own bodies and the complex chemistry that occurs within the various systems such as the gastrointestinal tract and the circulatory and nervous systems.

In this regard, there are five key concepts found throughout nature that John believes should form an integral part of any entrepreneurial venture in chemistry: -

A. **Triggered Change** – in nature things aren't only on or off permanently, rather they are on when needed and off when not e.g. hearing neurones (only triggered by the vibrations of sound) and gastric juices (only triggered when something that isn't our own bodies is present)
B. **Collaboration** – rather than adding on functional groups so that one molecule does everything, nature has numerous molecules working collaboratively and reciprocally e.g. in the digestive tract there is a multitude of different molecules along with bacteria and some yeasts to break down your lunch
C. **Alignment** – there is almost never a reactive collision using heat or pressure in nature. Nearly every action in biology happens in a semi-viscous watery environment with subtle diffusion and transitions rather than fast dramatic ones e.g. Oxygen transfer in your blood.
D. **Synchronicity** – in chemistry we are taught there are two distinct stages: materials undergo a reaction and create a desired product. However, in nature cells undergo thousands of reactions simultaneously rather than one at a time. When examining such reactions and transformations, it's vital to understand the nature of the changes, some of which are reversible and some irreversible, but all happen simultaneously and in harmony with one another.
E. **Diversity** – there has been a tendency to aim for high purity-based systems in chemistry and this is much easier to attain (and therefore also cheaper) with synthetics rather than biobased materials. However, nature hardly ever bases its systems on high purity; it actually thrives on molecular diversity as this will enable more resilience and adaptation for things like temperature or pH variation. If we can mimic this natural mixture approach, separation is not always necessary to achieve the same end – a highly lucrative prospect both financially and environmentally.

So how will chemists be able to move towards greener strategies? Certainly education is needed. John Warner helped to found Beyond Benign – an organisation that pioneers green chemistry resources for educators from high school through university to work-based learning. You can find lots of really helpful information, links and learning material on their site https://www.beyondbenign.org/

The materials on offer include open access curriculum guidance, experiments for students and much more – well worth checking out! There are also a multitude of textbooks available with one of the first *Green Chemistry, Theory and Practice* by Paul T Anastas and John C Warner published over 20 years ago by Oxford University Press US (ISBN 978-0-19-850698-0). It is a concise but excellent resource despite its age. More recently, the third edition of *Green Chemistry: An Introductory Text* by Mike Lancaster and published by the Royal Society of Chemistry in 2016 (ISBN 978-1-78262-294-9) provides a detailed overview of all chemical processes with extra detail on 'problem areas'. The chapter headings are: -

1. Principles and Concepts of Green Chemistry
2. Waste: Production, Problems and Prevention
3. Measuring and Controlling Environmental Performance
4. Catalysis and Green Chemistry
5. Organic Solvents: Environmentally Benign Solutions
6. Renewable Resources
7. Emerging Greener Technologies and Alternative Energy Sources
8. Designing Greener Processes
9. Industrial Case Studies
10. The Future is Green: An Integrated Approach to a Greener Chemical Industry

Both excellent publications contain a number of case studies. Sadly none of these are directly related to the aroma trades, but their relationship to practices within our industry are clear, particularly the section on pesticides in Lancaster.

It was heartening to attend a BSP event online in June, the first of a series putting the spotlight on responses to green issues in the industry, that explored what Firmenich were doing to address sustainability and the environment. This is written up in detail in this Newsletter. Please see the BSP website for details of further events. John Warner is also booked to speak at the upcoming online IFEAT Conference in November where there will also be a wealth of other excellent speakers. Please see the IFEAT website for details.

So, chemists – get inventing! The future of the planet is in your hands!! In the meantime, I will continue to do my bit by attempting to defy entropy by reusing my plastic tubs for as long as possible and putting out my recycling each week for my local council to hopefully process with as little environmental impact as possible.