Green chemistry & engineering becomes a movement……

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The Green ChemisTree Foundation, Mumbai, organized a two-day symposium and a series of seminars, workshops and industry interactions on the theme of 'Profitability from Industrial Green Chemistry and Engineering', under the banner of the 'Industrial Green Chemistry World (IGCW) – 2017 – Convention & Ecosystem', on October 5-6, 2017 in Mumbai.

Over 400 delegates from industry, research institutes, regulatory bodies and students, attended the event. Several departments of the government of India, chemical companies from various sectors in India and abroad, as well as the American Chemical Society-Green Chemistry Institute (ACS-GCI) supported the event.

Green Chemistry (GC) is about reducing waste, materials, hazards, risks, energy consumption and costs. It is one of the biggest cultural transformations that the chemical industry has seen and the pace of change has accelerated in recent years, including in India.

The seminars conducted in parallel covered: Pollution Prevention at Source – Green Chemistry Approach; Flow Chemistry; Emerging Tools and Technologies; Solvent & Reagent Selection Tool Guide; and CSIR-Industry interactions.

The Green ChemisTree Foundation also announced several awards for meticulously selected 'green' processes and projects from industry and research institutes in India.

'Innovation – We won't get from here to there without it'

Delivering the keynote address on 'Innovation – We won't get from here to there without it,' Dr. David Constable, Science Director, ACS-GCI pointed out that the chemistry enterprise as currently operating is completely unsustainable. The sustainability risks are real and the supply of several critical elements of the Periodic Table is not sustainable. Even today, chemists use 'old' chemistries to produce various products – about 54% have been in use since World War-I and 74% come from before World War-II. Manufacturing equipment too has not changed much – batch reactors, distillation columns, crystallizers, etc. used today are not very different from decades ago.

"Innovation is essential for designing new ways or new chemistries to design sustainable chemical processes," Dr. Constable noted. He called for "system-level thinking," and more "use-inspired" fundamental research. "Green is not synonymous with sustainability; efficiency is necessary, but not sufficient," he added, pointing to Jevon's Paradox (which states that when technological progress increases the efficiency with which a resource is used, the rate of consumption of that resource rises because of increasing demand). Sustainability research and education, he added, are multidisciplinary and collaborative. "Collaboration has been the hallmark of green chemistry development."

Dr. Constable listed several sustainable chemistry opportunities:

- Exploiting greater chemical diversity, especially from bio-based or renewable feedstock;
- Greater understanding and uptake of synthetic biology as a synthesis tool;
- New reactions focused on biologically derived molecules;
- Low energy direct conversion of carbon dioxide (CO_2) to methanol or higher carbon molecules;
- Sustainable production of hydrogen (H_2); and

- Closing the materials loop, i.e., using wastes as raw materials.

He also discussed several success stories of sustainable chemistries, including manufacture of propylene oxide (PO) using hydrogen peroxide (the HPPO process), metathesis technology, and the bio-succinic acid process from Myriant.

"There is a lot going on in green and sustainable chemistry, which is much more than just hazard and pollution reduction. Innovation and early design are key necessities for sustainable green chemistry," he concluded.

'Need to minimize folly…'

Mr. Ashwin Shroff, Chairman & Managing Director, Excel Industries Ltd., highlighted some GC initiatives undertaken by his company over several years. The company has discontinued use of carbon tetrachloride, a hazardous solvent; meets 50% of its power needs from wind energy; purifies & reuses 50% of wastewater generated; composts degradable solid waste and converts the non-degradable waste to synthesis gas.

Mr. R. Gopalkrishnan, Former Director, Tata Sons, spoke on the theme of 'How can smart people stop doing silly things?' He opined that the checks and balances of sustainability are disturbed today and this has led to the generation of lots of waste. "There is a need to go back to chemistry to find solutions."

Mr. Gopalkrishnan pointed to several examples from history on the folly of men: Mutiny of Indian soldiers in 1857; Partition of India in 1947; Extinction of Maori tribe on Easter Island and that of Aztec rulers in Mexico; the sinking of the *Titanic* in 1912; and the cold war incidence in the Bay of Pigs in Cuba. He reiterated the need to change mindsets or mind-frames to minimize folly. "It is necessary to improve our common-sense by retiring into 'ekanta' (solitude) and to remove the fear of failure from our minds," he noted.

Greener, sustainable process for Letermovir

Dr. Ingrid Mergelsberg, Director, Department of Process Chemistry, MSD (USA), noted that sustainable green chemistry is all about innovation, and gave several examples from Merck's strong legacy of innovation – including the hormone cortisone, and the anti-HV drug indinavir sulfate *(Crixivan).*

She presented the case study of process development of Letermovir – a life-saving drug for the treatment of human cytomegalovirus (HCMV). The original process route, licensed from Aicuris, had an overall yield of just 10%; about 20% loading of palladium; needed nine different solvents; had a Process Mass Intensity (PMI) of 700; and released an estimated 1,657-kg of CO_2 per kg of the drug.

The innovation focused on developing a process route having ease of operation, low cost, high yields & efficiency, ease of supply of raw materials, safety, reproducibility & robustness, freedom to operate and sustainability. The goal was to develop a process with zero waste by designing for atom economy, inventing new chemical transformations, and prioritization & optimization for sustainability. Several chemical reactions such as hydrogenation, amino-carbonylation, etc. were studied in high-throughput experiments with analyses in parallel. After trying several phase transfer catalysts, which had many disadvantages, the researchers went back and identified new chemical transformations and a new, stable, re-usable catalyst was developed.

Optimization for sustainability led to the development of the currently used greener process with simple, clean, homogeneous reactions; one-pot direct isolation of product; stable and easily recycled catalyst; use of only two solvents; and 91% yield. The PMI was reduced by 75%, while raw material costs were reduced by 93%.

Chemical industry under the 4th Industrial Revolution

While fossil fuels, computers and the Internet characterized the second and third industrial revolutions respectively, the ongoing 4th industrial revolution is about sustainability, digitalization and people.

"Today, there are multiple disruptions due to exponential innovation and convergence of technologies. These innovations also offer better operational efficiencies," noted Mr. Rafael Cayuela, Chief Economist, The Dow Chemical Corp. (USA).

Mr. Cayuela pointed to a report published by McKinsey, a consultancy, which showed that the chemical industry's R&D efforts between 2010 and 2015 generated 25% new chemistry and 75% incremental innovation. The main playground for the industry today is China, where the industry recorded the highest capacity growth of 14.3% CAGR between 2000 to 2014, in contrast to global capacity growth of around 4% CAGR. In absolute terms, the global chemical industry's capacity grew from 1,179-mtpa in 2000 to 2,156-mtpa in 2014, while that in China grew from 246-mtpa to 741-mtpa."

Dow Chemical, he added, has set seven goals to be achieved by the year 2025, of which two are related to GC, viz. delivering sustainable innovations and advancing a circular economy. He pointed to the use of high throughput experimentation, enabling nearly two million experiments to be carried out every year, to deliver on the goals for innovation.

'Green for good – every step counts'

Mr. Srini Srinivasan, Managing Director, Pfizer Global Supply and R&D, pointed out that 'going green' means taking steps – big or small – in making environmentally friendly and ecologically responsible decisions. "Positivity is key – believe there is good in the world. Take ownership of the problem and focus on developing solutions. Believe that you can bring in the change. As Mahatma Gandhi said, 'Be the change you want to see in the world," he noted.

In his view, 'Green Change' starts within the organization, with strong commitment at every level. "Green chemistry collaborations are happening at multiple forums: industry, supply chain partnerships, with industry associations, as well as in industry-government partnerships."

Mr. Srinivasan highlighted of Pfizer's green journey from 2001 to 2017, which resulted in significant benefits. For example, the company achieved a 98% reduction in the use of chloroform in manufacturing, besides reduction in carbon dioxide emissions, use of water & solvents, and waste generation.

Renewable resources: Expanding the chemists' toolbox

Dr. Julien Hitce, Process Innovation & Development – Advanced Research, L'Oreal (France), discussed innovation based on renewable resources. In the company's raw materials portfolio, as of 2016, 54% of ingredients were of renewable origin. "Specifically optimized transformations add value in the development of innovative cosmetic ingredients from biomass," he noted.

Sugars or polysaccharides are building blocks of nature and can be used in cosmetics for multiple functions by fine-tuning their physico-chemical properties. L'Oreal has developed, for example, a renewable ingredient from carrageenan, a polysaccharide, which is marketed under the tradename *ProXylane,* as a new anti-aging active for skin care products.

Other GC developments at L'Oreal include bio-catalysed carboxylation of phenols for preparation of resveratrol and its structural variants at optimized conditions.

GC – from a fad to a fixture

Mr. Jeffrey Whitford, Head – Corporate Responsibility & Branding, Merck KGaA (Germany), discussed the progress of GC at Merck, where more than 40 scientists work in nine GC centres to develop green alternatives for various products and packaging. More than 35 products have been re-engineered till date to make them greener.

Merck has also developed its own greener alternatives evaluation matrix called 'Quantitative Green Chemistry Evaluator' (DOZN) and has evaluated several raw materials, catalysts, solvents etc. including beta-amylase, Cyrene, bio-based acetone, butanol and para-xylene, using this metric.

The company also uses customer scorecards for green products. Its Environmental Opportunity Dashboard highlights potential solvent switches and packaging improvements.

Sustainable development – key to avoiding supply chain disruptions

Mr. Anil Kumar Jain, CEO – API Business, Sun Pharmaceuticals, stressed the need for sustainable development in the chemical industry, adding that in the past three years, more than 15% of problems in supply of pharmaceuticals have been largely due to production disruptions in factories in China.

Several plants there have been asked to close down due to heavy pollution. "Similar events occurred in Europe several decades ago, resulting in shifting of the chemicals industry from Europe to countries like China and India," he noted.

'Sustainability journey – good for business'

Dr. Julia Rowe, Group Sustainability Manager, Johnson Matthey (UK), discussed how the sustainability journey has been good for business.

The technologies offered by Johnson Matthey, he noted, address three big global challenges – improving air quality, efficient use & transformation of natural resources, and improving healthcare. Seven tough sustainability targets were set in 2007, including halving carbon intensity and key resources consumed per unit of product. The challenges faced were overcome by employee engagement (training of influencers and sustainability facilitator training programmes), rewarding success (JM Global Sustainability Awards launched in 2009), sharing success stories, and sharing expertise & promoting collaborations.

The successes of the past ten years include:

- 47% reduction in waster consumption at a nickel catalyst manufacturing unit in Taloja in 2015-16;
- Reduced greenhouse gas emissions by using solar energy – a 5.2-MW

solar plant in New Jersey (USA) supplies 20% of the site's electricity requirements; and

- In UK, 'zero-carbon' electricity is produced from offshore wind farms.

"The six targets set for the period were achieved to the level of 36% to 154%. During the ten years of transformation, the company improved environmental performance, made Johnson Matthey a safer place to work, many new business opportunities were identified, and bottom-line savings of £142-mn achieved," she noted.

Thriving on a GC culture

Dr. Ashutosh Agarwal, Chief Scientific Officer, Jubilant Life Sciences Ltd., noted that the company's R&D is focused on process intensification and bio-transformations, and leverages innovation to create cost-effective technologies.

Many initiatives have been taken for recycling & reuse of solvents, reagents and by-products; targeting zero discharge; and removal, substitution or minimization of hazardous chemicals in manufacturing processes. "Go Green initiatives have been implemented in supply chain management through reduced packing, procurement through e-commerce portal, etc." he added.

Jubilant Life Sciences has also installed a 105-KW solar power plant.

Ecotain – Clariant's approach to sustainability

Mr. Kumaresan Rajendran, South Asia Business Head, Clariant Chemicals India Ltd., noted that sustainability, as a guiding principle, is well anchored in Clariant and integrated into brand values and company strategy. "Sustainability is a value driver for business, managing risks and capitalizing on opportunities. It generates superior financial performance," he added.

The company has developed a comprehensive Portfolio Value Program (PVP) for screening its portfolio, increasing benefits and reducing impacts. PVP screening spans 36 criteria, of which 26 are related to Planet, six to People and four are about Performance. Products that contribute to more than 80% of sales turnover have already been screened and of these, more than 75% fulfil the company's sustainability criteria and about 140 have excelled and given the 'EcoTain' label.

The *GlucoTain* brand name, for example, has been given to an innovative range of sugar-based, sulphate-free, eco-friendly surfactants for cosmetics and personal care products.

'Reducing the environmental footprint of chemical processes'

Prof. Ashwini Kumar Nangia, Director, CSIR-National Chemical Laboratory (CSIR-NCL), Pune, highlighted some of the technologies developed at CSIR-NCL and transferred to industry. He referred to the significant waste generation in different parts of the chemical industry, as measured by the 'E-factor' (quantum of waste generated per unit of desired product) and pointed out that pharmaceuticals, which have small production volumes, have 'E factor' anywhere between 25 and 100. "From bulk chemicals to pharmaceutical products, the quantity of waste generated per kg of useful product increases substantially," he added.

Prof. Nangia discussed the impact of technologies developed and commercialized by CSIR-NCL with a few examples. Vinati Organics Ltd., for one, has become the largest manufacturer of 2-acrylamido-2-methylpropanesulphonic acid in the world, with 40% share of the global capacity, thanks to the technology developed at the laboratory. This chemical is used in paints & coatings, water treatment, adhesives and in the manufacture of polymers for enhanced oil recovery. Furthermore, intellectual property and patents developed by CSIR-NCL has been licensed to Benefuel (USA), for the production of fatty acid methyl esters and biofuels. CSIR-NCL has also developed technologies for conversion of glycerol to value-added chemicals such as glycerol carbonate (with 18% yield), glycidol (80% yield), etc.

The laboratory has also developed several other process technologies for

the production of dimethyl carbonate, 1,2-propanediol, polymer electrolytic membrane fuel cell, as also about 15 process intensification technologies for fine and speciality chemicals. It has also done work on various molecules that can be derived from crop waste. For example, glucose obtained from cellulose can be converted to gluconic acid, sugar alcohols, levulinic acid and hydroxyl methyl furfural.

"The themes for today revolve around energy management & benign environment, process intensification and continuous chemical processes, catalysis for high turnover and milder conditions, biomass feedstocks for value-added chemicals & fuels, raw materials sourcing, and by-products valorisation," Prof. Nangia added. "Solutions to problems do not come out of working in silos, but collaborations are necessary," he noted.

Chemical reactions of concern

Mr. Nitesh Mehta, Director, Green ChemisTree Foundation, and Founder-Director, Newreka Green Synth Technologies Pvt. Ltd., highlighted the results of a survey conducted to highlight chemical reactions of concern.

According to the survey, the top five chemical reactions or processes of concern are: nitration (using mixed acids), Friedel-Craft reactions (alkylation/acylation), diazotisation, cyclisation, sulphonation and chlorosulphonation. Other reactions of concern include bromination, azide reduction and imide formation. "These challenging reactions represent a huge opportunity for researchers," Mr. Mehta observed.

Opportunities in agrochemicals

Dr. Surendra Bhatia, Director, Sapec Agro India, pointed to the opportunities for GC in the manufacture of several large volume agrochemicals, including glyphosate (850-ktpa), mancozeb (150-ktpa), and chlorpyriphos (75-ktpa).

Glyphosate, the largest-selling pesticide, generates 5.6-kg of toxic waste per kg of the pesticide during its production. The new chemistry uses hydrogen cyanide and formalin to produce the key raw material, iminodiacetonitrile.

The largest-selling contact herbicide, mancozeb, was introduced in 1950. Its production capacity in India in 2016 was more than 120-ktpa and Dr. Bhatia pointed to several opportunities for improvement – development of continuous process in place of batch process; process for dust-free formulations, etc.

Chloropyriphos, a non-systemic insecticide introduced in 1965, requires an intermediate, which was available economically from China till last year (a business of more than Rs. 100-crore), but is not available today. "Production of this intermediate is an opportunity for new process development," he added.

Dr. Bhatia also discussed other opportunities in development of better processes for S-Metalochlor, sulfonyl urea, etc. Microencapsulation technology for agrochemical formulations is another opportunity, he pointed out.

Dr. Bhatia also highlighted the growing popularity of neem-based agrochemical formulations, and noted that with about 80-kt of neem seeds being collected every year in the country, this could be another significant business opportunity.

New chemical reactivities for future chemical sustainability

Prof. Chao-Jun Li, Professor in Green/Organic Chemistry, McGill University (Canada), pointed out that of the resources removed from the Earth, only about 10% are retained in the final product, while 90% are wasted during manufacturing. The grand challenge of sustainability stems from the fact that more than 97% of all manufactured products involve one or more chemical processes. "A major challenge for the future is chemicals syntheses. Catalytic processes, which can convert hydro-

SERB-IGCW Award winners

Category	Company/Institute	Applicant	Case study topic
MNC, large and medium-scale companies	Aarti Industries Ltd.	Mr. Smit Chauhan, Manager – Process	Manufacturing route change in hydrogenation
Small-scale industries	STEP Pvt. Ltd.	Dr. M.G. Palekar, Head – Strategy and Technology	Novel gas-liquid reactor, downflow gas contactor for efficient & effective, effluent treatment
Green Start-ups	Growtech Innovations India Pvt. Ltd.	Mr. Venkatesan Rajendran, Innovation Manager	Application of thermoelectric technology to replace CO_2 and R134a refrigerant
Technology Developers	Geist Research Pvt. Ltd.	Mr. Vikram Dhumal, Head – Technology	Recovery of anhydrous sodium sulphate from brine solution in caustic-chlorine industry
Student	CSIR-NCL	Ms. Nalinee Suryawanshi	Green approach to deep desulfurization using hydrodynamic cavitation
Researcher/Guide	CSIR -IICT	Dr. S. Venkata Mohan, Principal Scientist	Sustainable bio-hydrogen production from waste: pilot scale demonstration

carbons, carbon dioxide, carbon monoxide, hydrogen, nitrogen, biomass, and oxygen into useful chemical products using clean media, are needed today."

Prof. Li pointed to the challenge of using biomass for chemical transformations. "Biomass materials like cellulose, lignin, etc. are over-functionalized and new fundamental tools are necessary. How one can combine two different fully functionalized compounds to form another fully functionalized compound?"

Modern organic chemical science, he added, can be broadly classified on the basis of three types of reactions: protection & de-protection of groups; halogenation & dehalogenation; and functionalization & de-functionalization. "Is it possible to eliminate these types of reactions or minimize, for example, protecting & de-protecting of groups during chemical processes, to reduce waste?" he asked.

Prof. Li also observed that most of the top 200 drugs (by global sales) have at least one aromatic ring in their structure, while more than 30% have an amine group. Lignin, which constitutes about 30% of biomass, can be converted to usable aromatic compounds in large quantities, and can become the most abundant renewable aromatic feedstock. Likewise, fluorine is required in many drugs and agrochemicals and trifluoromethylated building blocks are widely used. "Simple and clean photo-induced aromatic trifluoromethylation reaction can be used to produce these building blocks," he added.

Mimicking nature

Mr. Mark Dorfman, Bio-mimicry Chemist, Biomimicry 3.8 (USA), discussed using nature's designs in commercial products. According to him, it is a misconception that chemicals are man-made entities that contaminate an otherwise chemical-free natural world. "Nature is alive with chemistry," he noted.

Mr. Dorfman discussed the methodology of bio-mimicry, which takes inspiration from the living natural world, rather than the inanimate natural world – be it structural colours in butterflies, insulation in bears, strength or hardness of oyster shells etc. The bio-mimicry innovation process, he noted, moves through several steps: scope identification, discovery, identification of deep patterns & non-critical attributes, etc. He pointed to several key success factors for developing a working prototype of bio-mimicry: commitment & leadership by the C-suite, lead chemists and creative R&D team; fostering creativity & imagination by thinking outside the box; ability to embrace failures; and dedicated resources.

"Some large global companies like Dow have shown interest in bio-mimicry," he added.

Embedding sustainability within research & innovation

Dr. Pascal Metivier, Senior Executive Vice President and Science & Technology Director, Solvay (Belgium), highlighted the company's proprietary approach to assess business sustainability risks and opportunities. The Sustainable Portfolio Management Map (SPM), plots risk levels (on Y-axis) against sustainability solutions (on X-axis), and can be applied to innovation projects.

The comparison of carbon footprint of products, he noted, is one way to evaluate them for sustainability. "Manufacturing processes are the main source of carbon footprint. Different processes have different carbon footprint values," he noted, and gave the example of polyamides wherein processes based on renewable resources lower the process carbon footprint. For example, the conventional process for Nylon 6 had a carbon footprint of 11.54, while the more sustainable process had a carbon footprint value of 10.84. Similarly, the manufacturing process for Nylon 66 having carbon footprint of 10.34 was improved to reduce it to 8.54.

Simplicity in process design

Dr. Sandeep Mohanty, Director – Process R&D, Dr. Reddy's Laboratories Ltd., discussed several aspects of a key strategy for improving chemical processes – subtraction from overcluttered designs. "Chemical processes need to be examined for reducing unwanted or unnecessary steps, for reduction of time cycle, etc. The process steps or unit operations should flow effortlessly from one to the other," he added.

Referring to global market for APIs, which is projected to reach $158-bn in 2017, with year-on-year growth of 4.2%, Dr. Mohanty sated that manufacturing processes are complex due to multiple isolation processes, which use water as well as organic solvents. "There is a need of simplifying these processes with Quality By Design, involving continuous improvements and process redesign."

As an example, he referred to the manufacturing of clopidogrel bisulphate before and after improvements with QbD. The benefits gained included 10% reduction in solid waste; 55% reduction in water usage; and 67% reduction in consumption of solvents.

Business value of life cycle assessment

Dr. Ashok Menon, Global Technology Leader, Life Cycle Assessment, Corporate Sustainability Division, SABIC India Pvt. Ltd., noted that many global companies have incorporated sustainability and life cycle assessment (LCA) in their business strategies.

LCA involves assessing global warming potential, impacts on environment, effect on fossil fuel depletion, ozone depletion, etc. It can be applied to find answers to questions such as which product is better on the basis of their carbon footprint; whether bio-based raw materials are better than fossil-fuel-based ones; or which technologies are better with respect to their environmental impact, etc. "This assessment helps in decision making and for making informed choices."

SABIC, he noted, is using LCA for making decisions related to technology development, feedstock strategy, development & marketing of sustainable products, etc. LCA also helps in taking decisions on future investments.

Dr. Menon also stressed the need to evaluate products from an LCA standpoint especially when identifying and using so-called green products. "The selected green alternatives may be giving out more carbon dioxide during its life cycle," he said. "The energy consumption of a smart phone and ICT infrastructure (for Internet) from a life cycle context is very close to annual energy consumption of a high-efficiency refrigerator!"

Barriers to GC

Dr. P.L. Srinivas, Head – API R&D – Bangalore, CIPLA Ltd., discussed several barriers to implementation of GC in the pharmaceuticals industry – economic, financial, regulatory, technical, organizational and cultural. Inadequate norms, enforcement by regulatory bodies, academia & industry disconnect, drug substance quality and complexity, etc. are other barriers to GC implementation, he pointed out.

Dr. Srinivas detailed how GC principles were implemented in research and innovation at CIPLA. Some steps taken included:

- Adoption of a 'top-down' approach by increasing awareness of GC in developmental teams;
- Review of existing commercial APIs with key metrics;
- Increasing accountability of individuals and teams by incorporating GC targets in their KPIs; and
- Promoting use of electronic notebooks having in-built, Internet-based 'E-factor' calculation.

He also provided a case study of an API (CS-101), the process for which had several drawbacks – use of hazardous chemicals, non-green solvents, mixed solvents for separations etc. After modifying the process using GC principles, the atom economy was improved from 85.9 to 82.3; E-factor reduced from 153 to just 53; and productivity improved from 26-tpa to 46-tpa.

In the second case study, GC principles were implemented in the four-steps manufacture of CS-102, another API, at the development stage itself. Organic solvents were replaced by water in the reaction steps; and the E-factor was improved from 240 for the innovator's process to 124 for the new CIPLA process.