CHAPTER 1

Green Chemistry Principles and Global Drivers for Sustainability – An Introduction

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1.1 Introduction: Drivers for Change

> *"We need to engineer ourselves out of a problem"*

Chemistry, chemical engineering and allied subjects have given modern-day society unprecedented access to chemicals, materials (articles) and energy predominantly derived from crude oil. Over the last forty years, global material use has tripled, with annual global extraction of materials growing from 22 billion tonnes (1970) to 70 billion tonnes (2010). As the global population is set to increase from 7 billion (2018) to 9 billion (2050), we will require about 180 billion tonnes of materials annually by 2050.[1,2] Adhesives and sealants have played a prominent role in the success of these materials. Significantly,

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many of these materials have been designed, engineered and manufactured to be long-lasting, one use only and not designed for re-use or recycling. They operate within the principles of a linear economy that takes, makes, uses and abuses materials, which at end of life (EoL) end up as waste, *i.e.*, cradle to grave. Often, the success or longevity of many petroleum-derived adhesives and sealants restricts disassembly, recycling and re-use at EoL thus adding to an increasing environmental waste burden. We have engineered ourselves into a problem based on an over-reliance on a relatively abundant, historical feedstock that has brought economic wealth but now even bigger environmental and social challenges.

Crude oil is a finite resource. In 2017, global proved oil reserves, *i.e.*, the estimated quantities of oil that geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under current economic and operating conditions, were 1696.6 billion barrels. Based at this level, only 50.2 years of global production are left.[3] We need to decouple human development efforts from ever-increasing natural resource use, energy demand, emissions and waste. Thus, the need for alternative sources of sustainable and renewable energy, materials and chemicals is immediate. A move towards more green adhesives and sealants derived from renewable resources, which use less or non-toxic additives, low VOCs (if any), low energy, and minimise waste both during manufacture and at EoL, is a positive step forward. The adhesives and sealants industry has been moving in this direction for many years through solvent-free liquid, 100% solid and waterborne formulations. *We need to engineer ourselves out of a problem* for the future of a sustainable 21st Century. Not to forget that often enough, adhesive bonding in itself is, from a sustainability point of view, advantageous over other bonding techniques, be it welding and soldering, be it “classic” mechanical assembly like bolting, screwing, and nailing or others.[4]

1.2 Biobased Markets and Trends[5]

The adhesives and sealants industry is moving towards becoming *green*. Historically, and today, many adhesives and sealants have been renewable or biobased resource-derived, for example, carbohydrates, tree resins, lignins, unsaturated oils and proteins. In 2017, globally, two industry sectors were dominant users of biobased adhesives and sealants (Figure 1.1), namely building and construction (250.77 kilo tons), and paper, packaging and board (356.56 kilo tons). Within the confines of the listed industrial sectors shown in Figure 1.1, over a 5 year period from 2018, the forecast predicts volume to increase at 4.49% compound annual growth rate (CAGR) reaching 1293.96 kilo tons by 2023.

Further analysis of available data on global trends by geographical region (Figure 1.2) shows that in 2017 the global biobased adhesives and sealants market reached 996.53 kilo tons with Europe (357.29 kilo tons) dominating closely followed by North America (304.91 kilo tons) and Asia-Pacific (269.22 kilo tons).

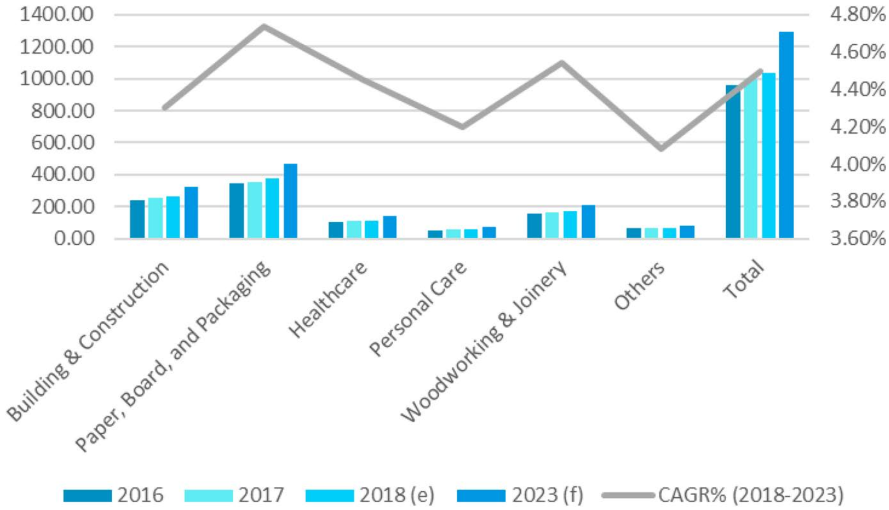

Figure 1.1 Global bio-based adhesives & sealants market by end-user industry (in Kilo Tons).

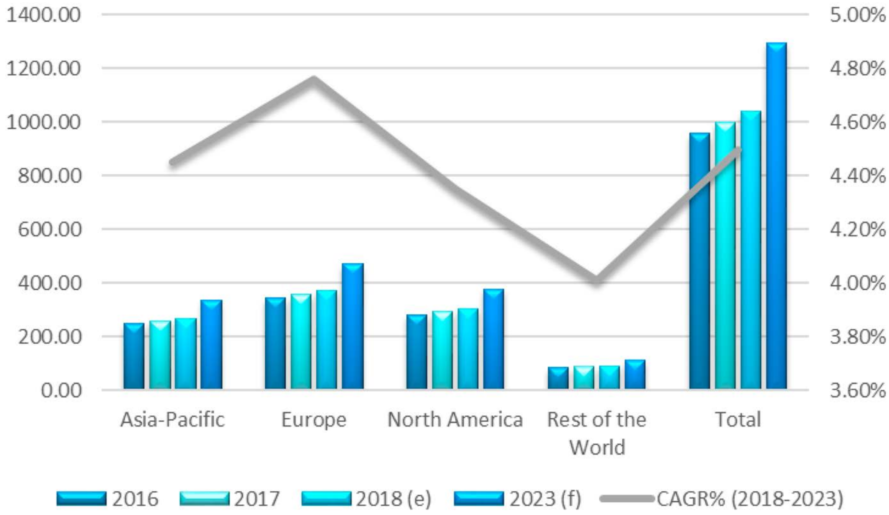

Figure 1.2 Global bio-based adhesives & sealants market (in Kilo Tons).

Importantly, the distribution (spread) and type of biobased raw materials are shown in Figure 1.3. Soy and starch-based raw materials for adhesives and sealants are dominant in this respect, occupying nearly 50% (565.39 kilo tons) market share of the total (996.53 kilo tons) in 2017, with the *others* category comprising natural rubber latex, protein adhesives, polylactic acid and polyhydroxyalkanoates in third place (252.32 kilo tons). Lignin-based adhesives[6] compared to the other categories are relatively low volume (63.82 kilo tons).

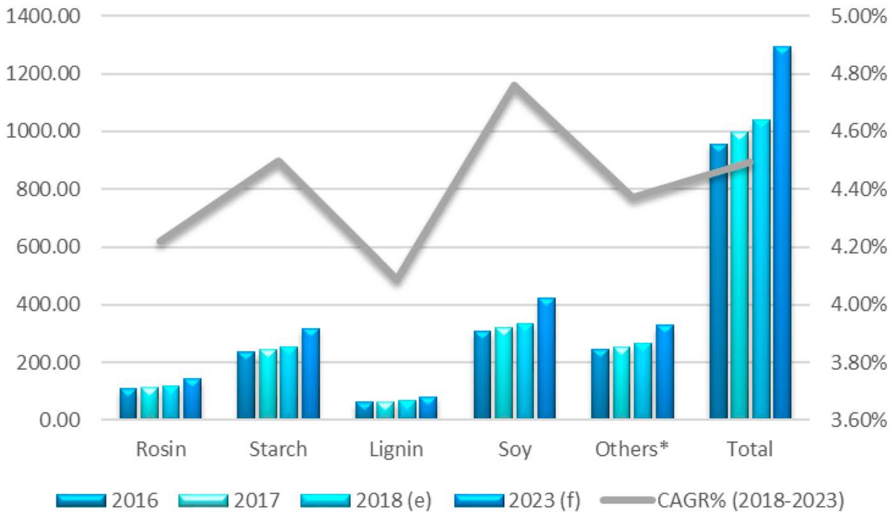

Figure 1.3 Global bio-based raw materials adhesives & sealants market (in Kilo Tons). Others* include natural rubber latex, protein adhesives, polylactic acid, and polyhydroxyalkanoates.

Despite these positive trends, the vast majority of adhesives and sealants are still petroleum-derived (synthetic), associated with environmental pollution, and complex formulations/products comprising volatile organic solvents (VOCs). The latter should not be ignored because their volume is cleaning, and priming of substrates prior to adhesion can be significant.

1.3 Circular Economy, SDGs, Waste, and Legislation

In 2015, the United Nations (UN) recognised the importance of sustainability in their report: 'Transforming our World: the 2030 Agenda for Sustainable Development,' which aims to protect the planet, people, alleviate poverty and enhance peace.[7,8] Seventeen Sustainable Development Goals (SDGs, Table 1.1) were actioned from this report with each goal further subdivided into several specific 'targets'. The SDGs comprehensively address the natural resource underpinnings of economic growth and human development across all aspects of resource use. For example, SDG 12 is of particular relevance to this chapter, as it deals with sustainable consumption patterns and production aiming to reduce or minimize the impact of waste, improve climate change and foster circular rather than linear economies by 'doing more with less', *i.e.*, a more resource-efficient society. Specifically: Target 2: By 2030, achieve the sustainable management and efficient use of natural resources, and Target 5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.

Table 1.1 UN sustainable development goals (SDGs).

SDG	Overview and action
1	No poverty: End poverty in all its forms everywhere.
2	Zero hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3	Good health and well-being: Ensure healthy lives and promote well-being for all at all ages.
4	Quality education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5	Gender equality: Achieve gender equality and empower all women and girls.
6	Clean water and sanitation: Ensure availability and sustainable management of water and sanitation for all.
7	Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy for all.
8	Decent work and economic growth: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9	Industry, innovation and infrastructure Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10	Reduced inequality: Reduce inequality within and among countries.
11	Sustainable cities and communities: Make cities and human settlements inclusive, safe, resilient and sustainable.
12	Responsible consumption & production: Ensure sustainable consumption and production patterns.
13	Climate action: Take urgent action to combat climate change and its impacts.
14	Life below water: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
15	Life above land: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
16	Peace and justice strong institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
17	Partnerships to achieve the goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development.

1.4 Green Chemistry: Guiding Principles

Despite all the good that chemistry gives us, unfortunately, it is tarnished with an image of danger, toxicity and pollution. Thus, a move towards green and sustainable chemistry from traditional red or brown chemistry is a positive societal and environmental step forward. In 1998, Anastas and Warner defined the term Green Chemistry, *i.e.*, the design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances, and established 12 guiding principles (Table 1.2).[9] Green Chemistry is both a philosophy and a methodology in the pursuit of sustainability.[10] In green chemistry, *nature* is both the supplier and the final customer. The design of new processes and products should be approached from this perspective.

As we seek sustainability and the practice of SDGs, the use of renewable feedstocks (Principle 7) is becoming more important for future chemical industries historically dependent on crude oil. This is also true for green chemistry with respect to adhesives and sealants. The terms biobased, bio-biobased and bio based are often used as a proxy for green chemistry in the guise of renewable resources (Principle 7), highlighted by the linear rise in publication and patents (including citations) since 2007 (Figure 1.4). There appears to be a positive movement towards renewable and biobased adhesives amongst the academic community.

However, it is important to note that many of the principles of green chemistry, in particular the use of renewable resources, pre-date Anastas and Warner. For example, Carver utilized agricultural crops and residues (peanut, sweet potatoes, *etc.*) to produce rubber as well as in many other applications.[11] 1n the 1930s, Ford manufactured (bio)plastic car parts from soybean residues and expressed the vision "*to build a vehicle affordable to the working family and powered by a fuel that would boost the rural farm economy*". His 1908 Model T engine was originally designed to run on 100% ethanol.[12,13]

1.5 Green Chemistry: Renewable Feedstocks to Biorefineries to Circular Bioeconomies

Biomass, both terrestrial and marine, plays an important role in the transition from a traditional petroleum-derived linear economy to a *circular bioeconomy*, offering a more sustainable approach to produce chemicals, materials and, to some extent, energy. According to the Nova Institute,[14] a circular bioeconomy can be defined as an intersection between a circular economy (efficient use of resources to reduce waste generation) and bioeconomy (replacement of fossil carbon by renewable carbon from biomass). Developing a circular bioeconomy based on biomass, and more specifically on waste biomass, has strong global support due to its short-term renewability, biodegradability, availability and societal advantages. McGalde and Ekins reported that the recycle time of agricultural/food waste biomass

Table 1.2 The Twelve Principles of green chemistry.[9]

Number	Principle
1	Prevention: It is better to prevent waste than to treat or clean up 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 syntheses: Wherever 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 (*e.g.* solvents, separation agents, *etc.*) should be made unnecessary wherever possible and innocuous when used.
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 ambient temperature and pressure.
7	Use of renewable feedstocks: A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable.
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 do not persist in the environment and 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: Substances and the form of a substance used in a chemical process should be chosen so as to minimise the potential for chemical accidents, including releases, explosions, and fires.

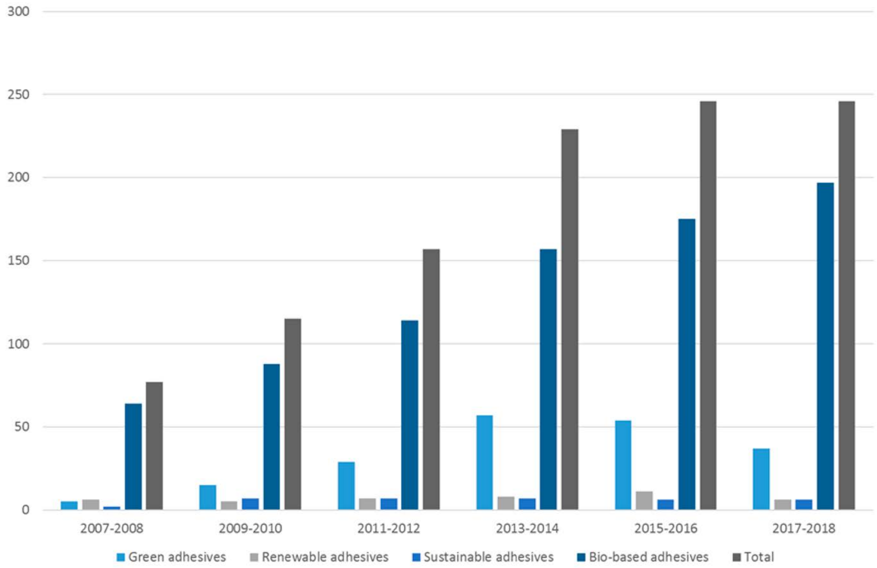

Figure 1.4 Number of publications (including patents and citations) based on key phrase search in Google Scholar from 2007 to 2018.

(3–12 months) can be up to 80x shorter than wood biomass (25–80 years) or 280 million times that of oil, gas and coal (more than 280 million years).[15] Circular bioeconomy strategies are now frequently incorporated in relevant national and international public policies. For example, in 2012, the EU Commission launched the *Bioeconomy Strategy*, which focused on sustainable growth and food security.[16] The strategy was revised in 2016, becoming more encompassing, to "*…also provide the framework for a sustainable, secure and cost-effective biomass supply for the bio-based and bioenergy sectors, by using waste, forestry, aquatic and other resources that do not compete with food production, while preserving healthy, productive and resilient land, seas and oceans, and by involving more effectively primary producers in the supply chain and value created*."[17]

Biobased or renewable feedstocks often imply biomass, which comprises cellulose, hemicellulose and lignin (also known as lignocellulosic) as its three main structural components in addition to starches, resins, oils and proteins. Their conversion into smaller chemical moieties upon application of an appropriate technology or process (fermentation, pyrolysis, liquefaction) yields potentially high-value downstream products (Figure 1.5) mimicking a conventional petroleum refinery but instead based on biomass, *i.e.*, a biorefinery. Although Figure 1.5 summarises a biorefinery with its main output as types of energy carriers, the preceding processes can be tuned to yield high-value chemicals and additives (see examples in Figure 1.3) for the adhesives and sealants industry.[18,19]

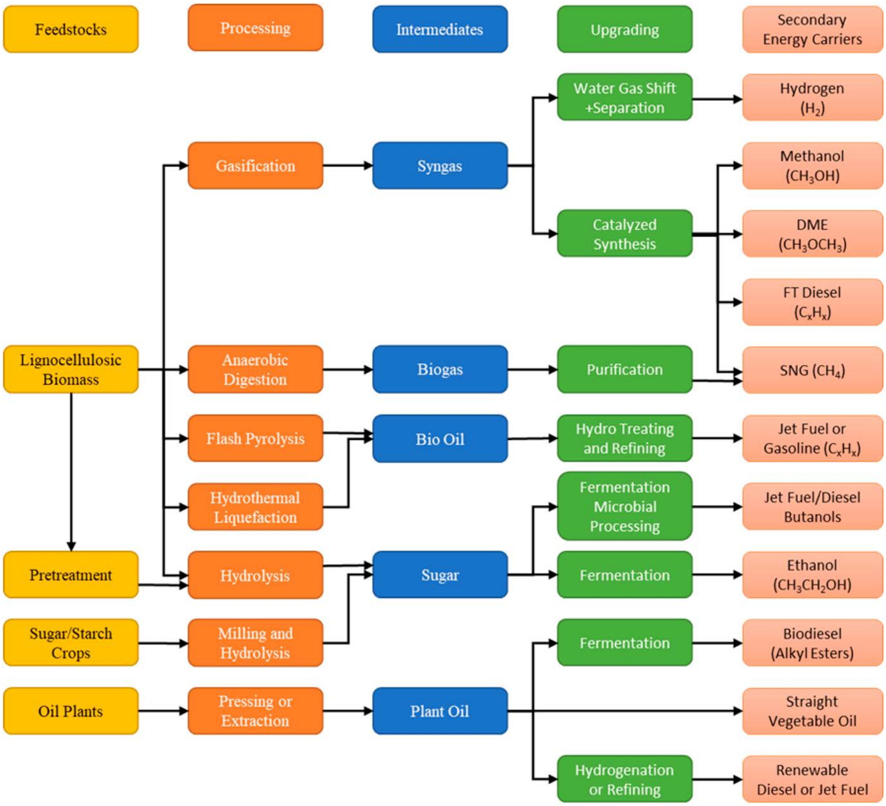

Figure 1.5 Overview of biomass conversion to chemicals and energy within the context of a biorefinery.[19]

Early biorefineries (Phase I, Figure 1.6) focused on single technologies and single feedstocks such as vegetable oil or starch, which were also in competition with food or feed.[18,19] Future biorefineries (Phase II and III) will be based on feedstocks that are non-food competitive, and will be able to receive flexible feedstocks and generate zero waste whilst outputting (bio)energy, chemicals and materials all year round. Future sophisticated biorefineries (Phase III) should be capable of producing low-value, high-volume (LVHV) products such as fuels, mainly including biodiesel and bioethanol, commodity products and generating high-value low-volume (HVLV) speciality chemicals and materials.

Feedstock logistics of biorefineries are quite different to those of a petroleum refinery where the feedstock is relatively uniform throughout the year. Biomass quantities need to be significant all year round and readily available, *i.e.*, smooth, uninterrupted feedstock logistics, irrespective of geographical location. Transportation costs of certain feedstock types such as agricultural

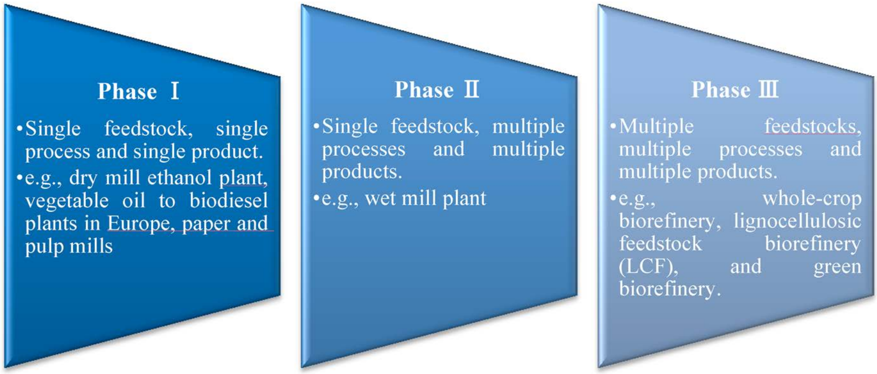

Figure 1.6 Phase I, II and III biorefineries.

grasses have to be minimised because of the low bulk density and high water content of biomass. Biomass densification will be important in developing future biorefinery infrastructures capable of processing biomass raw materials in substantial quantities while reducing operation costs. Additionally, wet biomass may need to be stabilised (*e.g.* dried) prior to long-term storage, which will significantly add to operational costs.

1.5.1 Green Chemistry: Green Metrics and Life Cycle Analysis (LCA)

Measuring the greenness of a reaction is now becoming an important facet in assessing the overall sustainability of a process or article.[19–24] Green metrics are usually applied in the manufacturing of an article whereas sustainability serves to provide a holistic overview, based on water, energy and land nexus, of broader environmental implications, *i.e.*, life cycle assessment or analysis (LCA). It is important to look beyond the laboratory (bench) or specific process as environmental issues can be hidden in upstream and downstream processes.

The greenness of a reaction should be based on a multitude of overarching factors: (i). Efficiency; (ii). Waste; (iii). Solvents; (iv). Catalyst/Enzyme; (v). Elemental Sustainability; (vi). Energy; (vii). Risk, Hazard and Health and Safety. Many of these are common practice in industry, especially adhesives and sealants. Manufacturing processes and practices are often lean and efficient based on profit/loss margins. Elemental sustainability may feature more prominently in the future, especially in specialty adhesives and sealants that may use precious metal catalysts or rare earth metals in their manufacturing operations. Many elements in the Periodic Table are under threat of insecurity of supply (availability), which may disrupt economic supply chains, welfare and jobs. These are often known as critical elements. Each country and geographical region will have its own critical metals list. Applying green metrics should critically consider the elements being used both in terms of virgin availability but also recovery from recyclate at EoL.

As discussed later, efficiency metrics are a poor measure of greenness as they do not take into account the risk, hazard and health and safety of reagents, auxiliaries, solvents, products and by-products, and the thermodynamics and kinetics of any reaction. There is now a wealth of information available (on-line tools and portals, Materials Safety Data Sheets (MSDS)) mainly in response to legislative drivers such as REACH (Registration, Evaluation, Authorisation of restriction of Chemicals) initially driven in the EU. To date, the European Chemicals Agency (Echa) have collected data on approximately 25 000 substances under the Reach (registration, evaluation, authorization and restriction of chemicals) programme. The impact of REACH now extends to South Korea (K-Reach), who have adopted similar guidelines.[23] The United States adopted The Frank Lautenberg Chemical Safety Act of 2016, which serves to modernize the Toxic Substances Control Act (TSCA).[22] Solvents that are discussed comprehensively in Chapter 2 will have a major impact on the greenness of adhesives and sealants. There are many green solvent guides available but this list is limited whilst at the same time there are an increasing number of solvents under the radar of REACH as they are Substances of Very High Concern (SVHC). The adhesives and sealants industry has moved towards reducing VOCs through increasing the number of water-borne formulations. However, often, incompatibility (immiscibility) with other components in the formation, loss in performance and increased drying times limit simple solvent substitution.

1.5.1.1 Green Metrics

1.5.1.1.1 Yield (%). Yield (eqn (1.1)) is commonly used in chemistry and it expresses the number of molecules (mols) of product with respect to the number of molecules (mols) of limiting reagent.

$$\%\text{Yield}=\frac{\text{moles of product}}{\text{moles of limiting reactant}}\times 100 \tag{1.1}$$

% Yield is a misconstrued form of efficiency that is still the main domain of our education system. However, it fails to recognise the total number of reagents, auxiliaries, solvents, processing aids used and by-products (often classed as impurities) formed. A high yielding non-stoichiometric reaction using several auxiliaries in reality is very inefficient.

1.5.1.1.2 Atom Economy. The atom economy (AE, eqn (1.2)) purely focusses on the per cent conversion of atoms from all reagents, except inorganic reagents, into products. It does not take into account reagent stoichiometry, *i.e.*, it ignores the molar excess of reagents [12] and solvents [13]. Addition (A + B to C) and rearrangement (A to A′) reaction types often typify a high AE.

$$\frac{\text{MW of product(s)}}{\text{MW of all reagents}}\times 100\% \tag{1.2}$$

1.5.1.1.3 Reaction Mass Efficiency.[21,22] The Curzons Reaction Mass Efficiency (RME, eqn (1.3)) is an improved and/or more comprehensive form of AE that considers the yield (mass of isolated product) with respect to the total mass of reactants within a balanced equation, thus taking into account reagent excess(es). When there is a stoichiometric balance, the RME simplifies to the product of yield and atom economy or the mass of isolated product with respect to the total mass of all reactants (eqn (1.4)), and it is termed the maximum or Kernel RME. However, due to the potential difficultly of differentiating between reagent and auxiliary, the RME can be misconstrued. Andraos further refined the RME equation (generalised RME, eqn (1.5)) to take into account all reactants, reagents, processing aids, solvents and purification aids.

$$\text{Curzons RME} = \text{Yield}\times\text{Atom Economy}\times 1/\text{SF} \tag{1.3}$$

$$\text{Kernel RME}=\frac{\text{mass of isolated product}}{\text{total mass of reactants}}\times 100 \tag{1.4}$$

$$\text{Generalised RME}=\frac{\text{mass of isolated product}}{\begin{array}{l}\text{total mass of reactants, reagents,}\\ \text{solvents, processing aids....}\end{array}}\times 100 \tag{1.5}$$

1.5.1.1.4 Mass Intensity and Process Mass Intensity. The Mass Intensity (MI, eqn (1.6)) and Process Mass Intensity (PMI, eqn (1.6)) are possibly the best metrics as they take into account all reagents, reaction stoichiometry, solvents (water for processing is not considered), work up and purification. The PMI is used for multi-step processes or cascade reactions. The ideal PMI is 1, *i.e.*, no waste is produced (100% closed loop recycling) and all materials are integrated into the product.

$$\text{Process mass intensity}=\frac{\text{total mass in a process or process step}}{\text{mass of product}} \tag{1.6}$$

The PMI can hide serious issues so more often than not it is important to calculate the MI for each step. Improvements in metrics are easier to follow if data can be separated out, for example breaking down mass inputs into categories for Process Mass Intensity calculation and hence obtaining a PMI value for solvents, PMI for water and PMI for all other reagents, as well as a total figure. This can also help identify environmental 'hot spots' in terms of the largest contributor to the overall figure.

1.5.1.1.5 Environmental Factor.[24] The Environmental factor (E, eqn (1.7)) is the amount of waste generated in a process with respect to product formed. Low tonnage (10–1000 tonnes) industries such as pharmaceuticals have very poor (high) E-factors often ranging from 25 to >1000, whereas the oil refining industry (10^6–10^8 tonnes) is highly efficient with E-factors <0.1. The E-Factor takes the chemical yield into account and includes all reagents, solvent losses, and all process aids, excluding water.

$$E_m = \frac{1}{\mathrm{RME}} - 1 \text{ or } \frac{\text{total mass in a process or process step} - \text{mass of product}}{\text{mass of product}} \tag{1.7}$$

The number of metrics applied by individual industries will also be different. Thus, regional, global and national adhesives and sealants consortia should consider adopting consolidated green chemistry and sustainability benchmarks similar to Chem 21, an EU-funded project aimed at improving the greenness of the pharmaceutical industries.[21]

The EcoScale somewhat bridges green metrics and sustainability.[25] The Ecoscale is "a semi-quantitative tool to select an organic preparation based on economical and ecological parameters". The EcoScale considers six distinct categories: (i) isolated product yield; (ii) cost of chemicals; (iii) safety concerns; (iv) technical set-up; (v) reaction conditions (temperature/time) and (vi) reaction workup/purification methods. The scale starts at 100 (an ideal synthesis) and then deducts points based on concerns in any of the six categories, for example, the penalty associated with a non-quantitative reaction yield is (100 − % yield)/2, *i.e.*, a yield of 90% equates to 5 penalty points. The EcoScale is a good introduction at the bench level and has been modified for industrial purposes.

1.5.1.2 Life Cycle Assessment (LCA)

To date, life cycle assessment (LCA) is the most extensive method of reporting the sustainability characteristics of a new/existing product or process from an environmental, techno-economic and social perspective, *via* Environmental LCA (E-LCA), Life cycle costing (LCC) and Social LCA (S-LCA). Most value-added products/services and high-value products in the industrialised market must have their sustainability practices assessed, quantified and reported as a way of showcasing this commitment to environmental and societal well-being, in addition to the well-being of the company. LCA has captured the attention of both administrative authorities (*e.g.*

governments) and appropriate regulatory authorities, such that sustainability practice reporting has commonly become a part of corporate social responsibility (CSR). There are set international standards within the ISO standards for Environmental management (ISO 14000), ISO14044 to be specific, that provide sufficient guidance to undertake life cycle analysis in a systematised fashion. Other guidance documents such as the Product Environmental Footprint (PEF) worked with LCA experts and consultancies to develop Product Environmental Footprint category rules (PEFCRs) for specific product categories. The ISO standards have been adapted by the European Standardisation committee (CEN) to develop and provide guidance for EU operators on undertaking sustainability assessment of products and services, referring to the EN16760 document highlighting the characteristics to be captured through a dedicated LCA.

Life Cycle assessment (LCA) is a comprehensive tool that includes the environmental impact of any product or process using its material/energy requirements as input specifications. The depth of such an analysis is assessor-specific and can be conducted at different levels:

1. Cradle–Cradle: Raw material generation to recycle product;
2. Cradle–Grave: Raw material generation to product end life;
3. Cradle–Gate: Raw material generation to factory gate.

LCA is about assessing and quantifying the various impacts (including global warming potential, resource depletion, acidification potential, eutrophication potential, land use change, biodiversity loss, and eco/human toxicity) arising from the use of all the materials and energy (life cycle inventory) consumed by an assessed product or process. Life cycle assessment does not provide a single score but allows the LCA user to weigh and prioritise the magnitude of the quantified impacts, based on the scenario of analysis (for example, water scarcity if the product assessed is based in South Africa). The final life cycle impacts of the product or a process may, therefore, vary depending upon the type of allocation chosen by the assessor. Life Cycle Assessment (LCA) is an effective tool to evaluate environmental impact and product sustainability, and its versatility allows application in financial feasibility studies[26] through elaborate techno-economic environmental study. Life cycle assessment is undertaken following four (or five) steps:

1. Definition of goals and scope;
2. Development of life cycle inventory;
3. Life cycle impact assessment;
4. Result interpretation and discussion;
5. Optional (defined by user) – Iterative product or process optimisation.

Owing to the enormity of possibility in defining a product's sustainability characteristics, the very first step is to assess and create a system boundary (*e.g.* cradle–gate or cradle–grave). An example of all the stages that are covered under "Cradle to grave" assessment is:

1. Raw material (biomass) acquisition;
2. Transportation: Field to pre-processing plant;
3. Pre-processing phase – for the preparation of secondary feedstock;
4. Transportation: Pre-processing plant to refinery;
5. Refinery;
6. Packaging and storage;
7. Product Distribution – transportation to local industries or whole-sale retailer;
8. Distribution of final product distribution;
9. Product consumption;
10. Used product/waste disposal.

A number of tools are available to undertake a holistic environmental impact assessment of a product or products in real-time, however, it is at the discretion of the assessor to choose between these tools or develop an LCA model of his/her own. Some of the most popular tools are Simapro from PRé consultants, GABI LCA and Open LCA, which (except Simapro) are free downloadable LCA software. Environmental Input-Output LCA (EIO-LCA) may be utilised by studies on the environmental impact of products incorporating national and international commodity trade statistics. For custom-build models, an assessor may want to incorporate life cycle inventory and databases such as the US life cycle inventory database or Ecoinvent (from the Swiss centre of Life cycle inventories). LCA will be at the forefront of future sustainable business decisions.

1.6 Conclusions

Trust, transparency and traceability will be a future paradigm for sustainable inks, coatings, adhesives and sealants. Both the principles and practices of green chemistry will be in concert with LCA. As more data are gathered and their reliability improved, trustworthiness will increase. The predicted future market growth coupled with inter-related global megatrends will continue to see more materials on our planet. Designing new materials with disassembly in mind at the outset coupled with the use of renewable resources and clean technologies will dictate a new mindset of sustainable scientists, engineers and business leaders of the future.

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