Chapter 11.

Education and training for industrial biotechnology

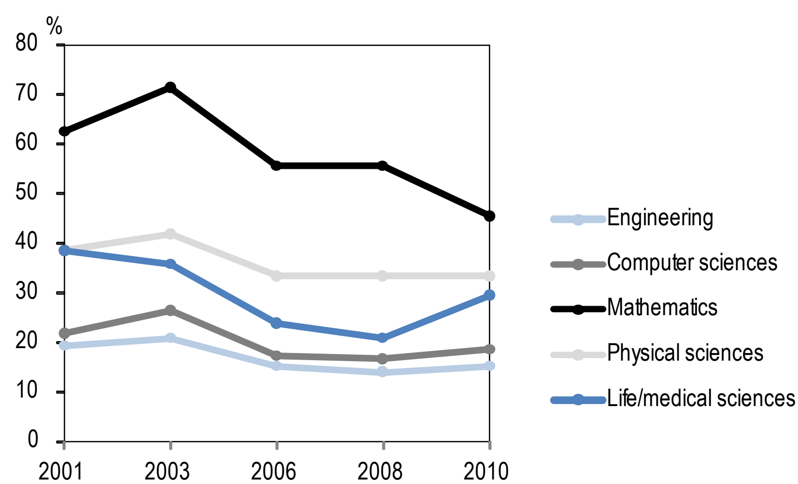
This chapter examines education and training for industrial biotechnology, a field that calls for education outside of normal disciplinary boundaries. Many factors in the education and training of industrial biotechnologists point to multi-disciplinarity. This has been discussed many times, but has been elusive in practice. The most obvious combination of skills needed is synthetic biology or genetic engineering with "green" chemistry, with the reduction-to-practice skills provided by chemical engineering. Other mathematical skills are also important. But for employment in small companies, employees also need to be flexible and willing to multi-task and get soft tasks done. This often does not suit a PhD graduate as doctoral training remains specialist, long-term and driven by publication. Although these issues could have been part of a capacity building discussion in this book, the significant policy implications warrant their own chapter.

Introduction

OECD analysis suggests that innovation thrives in an environment characterised by a few key features, including a skilled workforce (OECD, 2015). Skills will be central to enabling bio-production due to the newness of the subject, its multi-disciplinary nature, the complexity of biology and bio-production, and the need for many stakeholders with different skills. Jobs for the workforce, not only research jobs, are a major goal of bio-production. This will only work well by rethinking education.

A key discipline of industrial biotechnology is microbiology. Life sciences PhD-level education remains focused on training for academic careers (American Society for Microbiology, 2013). However, data from 2010 published in the National Science Board (NSB) 2014 Science and Engineering Indicators show that a mere 29% of newly graduated life science PhDs will find a full-time faculty position in the United States (Figure 11.1). A recent review also confirmed that growth in the number of US post-doctoral researchers far exceeds the growth in the number of tenure-track job openings (National Academy of Sciences, 2014a). There are simply too many PhD students and too few senior posts (Nature, 2016). On the positive side, then, post-graduates should have plenty of choices for entry into industrial biotechnology. However, in microbiology, the field is overwhelmingly dominated by medical microbiology.

Figure 11.1. **Likelihood to work in academia for newly graduated PhDs**



Note: The low figures for engineering and computer sciences reflect the greater likelihood that these PhD graduates will enter industry.

Source: Delebecque and Philp, unpublished data.

The problems are far from new. As far back as 1995, a report expressed the need for change in the education of scientists and engineers (National Academy of Sciences, 1995). This report was concerned that the United States was producing too many PhDs. It said that industry often complained that graduates were too specialised to accomplish the range of tasks they would be confronted with. Also, when scientists form small biotechnology companies, they are often placed in a managerial role in which they may have no training or know-how (Corolleur et al., 2004). This has all brought about a call for a new type of PhD, one that offers much more breadth and flexibility.

The challenge of multi-disciplinary education

Traditional scientific education and training has remained divided by disciplines such as microbiology, chemistry and computing. The long-standing conundrum of multi-disciplinary education is the need for both breadth and depth. The challenge to higher education remains on many levels. For example, a central theme in bioeconomy strategies is sustainability. Training in sustainability itself begs multi-disciplinarity as some of the depth skills needed are systems thinking, strategic planning, and evaluating environmental, social and economic performance. This educational conundrum for sustainability (Mascarelli, 2013) is the same for industrial biotechnology: how to make the inter-disciplinary approach not only substantive, but also practical for early-career scientists.

Life sciences industry-wide issues

Some of the life sciences-wide industry issues are clearly crystallised in an American report (CBSI, 2013). Employer interviews identified several industry-wide gaps in the capabilities and talent of the workforce pool and proposed reasons:

- The life science industry has a decreased need for deeply trained senior scientists. There is an over-specialisation surplus, whereas employers are looking for a workforce with greater breadth and more soft skills.
- Academic programmes are training students by discipline and not by problem-solving, which typically requires cross-disciplinary skills and capabilities.
- Apprenticeships and long-term training programmes are lacking.

The UK biopharmaceuticals industry recently highlighted major skills gaps in mathematical and computational areas. These have emerged due to the rapid development of new disciplines such as systems biology and health informatics (ABPI, 2015). For the industrial biotechnology industry, the same holds true. The following sections address some specific and critical training gaps to foster industrial biotechnology and synthetic biology-based manufacturing. They attempt to examine the future look of the workforce and related research base if this activity gathers momentum in response to societal grand challenges. This may guide governments in directions for higher education.

The critical workforce gaps in bio-based manufacturing

Finding biologists is not the most difficult task for bio-based manufacturing. Automation engineers specialising in high-throughput strain production critical to synthetic biology-based manufacturing are rare. Managing automated systems will have to be a skill set for graduates in biology and chemistry in the future (Extance, 2016). For a long time, it has also been difficult to find fermentation staff: this is the province of the biochemical engineer, who combines the mathematics of cell growth with bioreactor and bioprocess design. And yet bio-manufacturing is the common operation that links together all the different market sectors of the world's biotechnology industry.

Perhaps hardest to find of all are employees well versed in experimental design and statistics, especially now that large data sets are becoming more common. Big data is creating an imperative for more complex design that enables fewer experiments and trials. Scientific irreproducibility – the inability to repeat others' experiments and reach the same conclusion – is a growing concern. Yet few early-career researchers receive formal instruction on topics like experimental design and flaws in statistical analysis (Baker, 2016).

This diverse group of employees is essential for a functional synthetic biology-based production plant, but remains rare as this business sector is a small niche. As sector growth is difficult to forecast, it challenges governments to predict how to invest in and reform higher education to create a workforce that matches the growth dynamics of the sector.

Bioinformatics may be a major roadblock

The bottleneck for the growing industrial biotechnology industry is shifting to bioinformatics and data mining. Data mining tools akin to the ones revolutionising social sciences and linguistics will become essential. The Short Read Archive at the US National Center for Biological Information is set to exceed a petabyte (National Academy of Sciences, 2013). As high-throughput sequencing is increasingly deployed across research organisations, hospitals, biotechnology facilities and companies, the acquisition of genomic information will also burgeon. DNA synthesis costs have tumbled between 2014 and 2016. These price decreases, combined with advances in next-generation sequencing, are increasing the need and role of advanced software design tools.

"Dry lab" skills have traditionally been isolated from "wet lab" ones. Nevertheless, bioinformatics requires deep knowledge of biology theory and mathematics/computing. These fields are usually not taught in depth in the same programme in higher education, and this is but one more challenge to be overcome.

The scientist as engineer

Engineering education depends on several key concepts that have been largely missing in biotechnology (Panke, 2008): comprehensiveness of available relevant knowledge; orthogonality; hierarchy of abstraction; standardisation; and separation of design from manufacture. Systems modelling and design are well-established in engineering disciplines, but until recently have been rare in biology. The sheer complexity of biology has also hindered development of its formal mathematics. Synthetic biology has started to bridge the gap between biology and engineering (Liu, Hoynes-O'Connor and Zhang, 2013).

The education of a biologist, which still focuses more on the needs of research, has been dominated by a more descriptive tradition. This contrasts with engineering, dominated by a much more quantitative tradition, and the need to standardise and reduce complexity to practice.

However, this comes at a time of widely conflicting attitudes to engineering education. For example, only 4.4% of the undergraduate degrees awarded by US colleges and universities are in engineering. This compares with 13% of similar degrees awarded in key European countries and 23% in key Asian countries (National Academy of Sciences, 2014b).

With the continuing relationship between technology and discovery, Botstein (2010) contends that cell biologists in the next 50 years will have to be conversant with a broader range of concepts. This will range from physics through chemistry to genetics. However, they will especially need to know mathematical and computational methodologies that drive technology development.

The quantitative theoretical and computational component represents a fundamental departure from the tradition of the life sciences. Nevertheless, Tadmor and Tidor (2005) stressed that modelling should not be construed as a replacement for experimentation. Indeed, large stores of practical and theoretical knowledge are essential for one to function in a laboratory environment. But creating this depth of laboratory skills is among the most expensive and time-consuming elements of higher education. It leads back to the dilemma of breadth versus depth versus adaptability.

The chemical engineer as a role model?

Chemical engineers have played a tremendous role in generating and transferring the enormous benefits of the chemicals industry to society. The mathematics and thermodynamics of chemical engineering enabled the transfer of chemistry from the laboratory to full-scale industrial production, using crude oil as the raw material. For industrial biotechnology to fulfil its promise in a bioeconomy, these skills will be essential, with the new raw material being biomass. Chemical and biochemical engineers are key elements of the future bioeconomy because they alone can set the production agenda, knowing the process, energy, materials and cost elements (Woodley et al., 2013).

The chemical engineering curriculum is already full. Chemical engineering students may not wish to have industrial biotechnology in the undergraduate curriculum. Such a move could divert them from their main objective: to get certification to practice in the chemical and petrochemical industries. This may indicate a niche for training chemical engineers at Master’s level in industrial biotechnology.

Synthetic biology education: Another key “inter-discipline”

The education system has been responding to the needs of the growing synthetic biology community. The number of courses in synthetic biology has grown at a tremendous rate, with at least 100 institutions involved (Delebecque and Philp, 2015). However, many do not focus on industrial production. Therefore, industrial biotechnology courses, and organisations teaching them, are still very much pioneers.

Beyond science and engineering

Given the history of the genetic modification (GM) debate, such matters as public perception will also shadow industrial biotechnology and synthetic biology. There is already evidence that political and economic pressures will guide development of synthetic biology (e.g. Rai and Boyle, 2007). Kuldell (2007) argued that educational efforts that fail to equip students for these aspects of the emerging discipline are unsound. Public engagement, though fraught, is necessary for the acceptance of synthetic biology and industrial biotechnology more broadly. Public engagement is weakened by a lack of a standard approach (National Academy of Sciences, 2016). Policy makers could include social scientists and ethicists in strategies for developing and encouraging the uptake of bio-based products, and have this embedded in education. On the other hand, public engagement should not become a “mode of governance” of research (Kuntz, 2016).

To make employees fit for the workplace, this education also needs to encompass other practices such as regulatory compliance, risk assessment and biosafety, and good manufacturing practice (GMP). These practices are not academic research disciplines. But they can change rapidly, with far-reaching consequences for a small company. In-house training in GMP, for example, takes up considerable time and human resources. It can be a burden for small companies.

The many faces of regulation

Bio-based production creates regulatory challenges across boundaries as well. The metabolically engineered microbes (i.e. process) are subject to GMO regulation. At the same time, the chemicals and fuels (i.e. products), often being drop-in substitutes for fossil-derived materials, are subject to chemical regulations. These include the Toxic Substances Control Act (TSCA) in the United States and Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) in Europe.

Some approaches to industrial biotechnology education and training

The US NSF Center for Biorenewable Chemicals, a third generation Engineering Research Center (ERC) established at Iowa State University in 2008, is a classic approach to industrial biotechnology education and training. It includes five core partner universities, two affiliated research centres, four international partner institutions, and multiple industrial partners and pre-college entities (CBIRC, n.d.). The ERC's mission is based on research and education principles that seek to transform the existing petroleum-based chemical industry into an industry based on renewables (Haen et al., 2012). It offers courses for school teachers, through undergraduate and graduate education.

Undergraduate courses: Preparing the way

It is probably too early for entire undergraduate degrees to train biologists in industrial manufacturing. However, relevant science undergraduate degrees could be re-designed to serve as a platform for post-graduate study. For example, one of the key disciplines, microbiology, has curricula overwhelmingly dominated by medical microbiology. A re-orientation of microbiology undergraduate education could include, apart from the core microbiological skills, quantitative skills that are important for success in industry. Students so equipped with skills in calculus, linear algebra, statistics, large dataset management and programming (American Society for Microbiology, 2013) would be better disposed to embed industrial aspects of biotechnology.

In Canada, two universities are strengthening undergraduate programmes in biotechnology. The faculties of science (biochemistry) and engineering (chemical engineering) at the University of Ottawa jointly offer an undergraduate biotechnology programme. The University of Guelph offers an undergraduate programme in biological engineering that focuses on fundamentals in biomaterials science, bio-systems analysis, bio-mechanics, instrumentation and digital control. The programme can be tailored to explore interests in the production of renewable fuels such as ethanol and biodiesel; sustainable bioplastics made from plant materials; the extraction and stabilisation of nutraceuticals to provide health benefits; or the manufacturing of safe food products.

Taught and Research Master's

Industrial biotechnology lends itself well to a research Master's degree, emphasising practice-led research combined with relatively few taught modules compared with other graduate degrees. This sort of degree is designed in most cases to prepare students for doctoral research. However, it is also useful for those considering a career in the private sector where research is a key focus, but a PhD is not specifically required.

Various institutions around the world have begun to offer graduate degrees related to industrial biotechnology. The University of Georgia Master of Biomanufacturing and Bioprocessing degree (UGA, n.d.), a two-year programme, claims a unique focus on the full bio-manufacturing experience with hands-on training and exposure to industrial grade equipment. Its curriculum includes academic courses in science (e.g. biofuels/biochemical, pharmaceuticals manufacture) and business (e.g. finance, supply chain issues and manufacturing practices). It also offers professional training with cutting edge companies through case study projects and internships. Instead of producing a traditional thesis, students complete a research project during the summer of year one and a 400-hour industry internship during the summer of year two.

The La Trobe University (Australia) Master of Biotechnology and Bioinformatics focuses on the interface of molecular biology and information technology. It uses the power of computing to tackle biological and medical problems. The need for bioinformatics graduates will increase as computational tools are increasingly incorporated into bio-production.

The University of Cagliari (Italy) Master in Chemical and Biotechnological Process Engineering combines the skills of chemical engineering with the needs of the biotechnology industry. A goal is to teach students how to use the increased knowledge of chemical, physical and biological sciences to develop advanced mathematical models for chemical and biotechnological processes.

The Grenoble Ecole de Management (France) Master Specialised Management of Biotech Companies aims to provide specific managerial skills and understanding of issues related to the sector, as well as training in change management and the specific challenges of the biotechnology sector.

The University of Guelph, Ontario Master of Biotechnology programme brings together the Department of Molecular & Cellular Biology, and the Department of Management to offer courses in business skills (e.g. commercialising innovations) in addition to deeper scientific training.

Massive open online courses

The traditional on-campus experience could be radically changed by the explosion of massive open online courses (MOOCs), which will enhance classroom and laboratory work. The evidence for the impact of MOOCs is still embryonic. More analysis is needed as greater experience is acquired with their use. A number of MOOC platforms, such as Coursera (Coursera, n.d.) and edX (edX, n.d.), now propose a wide array of classes spanning engineering to molecular biology and all the building blocks in between that can provide the basic toolset to start practising engineering biology. A specialist MOOC for industrial biotechnology is offered jointly by the Technical University of Delft and the University of Campinas (Box 11.1).

Box 11.1. **edX course in industrial biotechnology**

The edX course in industrial biotechnology is a joint initiative of TU Delft (Netherlands), the international BE-Basic consortium and University of Campinas (Brazil). It provides the insights and tools for the design of sustainable biotechnology processes. Students use the basics of industrial biotechnology for design of fermentation processes to produce fuels, chemicals and foodstuffs (BE-Basic Foundation, 2016). Throughout this course, students are challenged to design a biotechnological process and evaluate its performance and sustainability.

Combining edX with other relevant courses can build the broader education that bioeconomy and industrial bio-based manufacturing seems to need. For example, TU Delft offers another MOOC course on responsible innovation. This discipline considers new technologies that are being developed in response to social challenges (e.g. food safety, smart cities, sustainable energy and digital security).

The TU Delft MOOCs are offered through the online edX platform, where MIT, Harvard and other universities have been making courses available to anyone with an internet connection since 2012. TU Delft chose to use edX partly because the platform allows publication of materials with an open licence, making it possible for others to use the materials.

Arguably, MIT pioneered online learning, building on research that consistently showed that students perform better when they take both traditional and online courses than when they take only one (National Academy of Sciences, 2014b). The MIT and Harvard-owned edX MOOC platform differs from other such platforms as it is non-profit and runs on open-source software. Unlike the traditional lecture, each lesson is a ten-minute video on a single concept followed by self-assessment tools.

MOOCs are easily scalable and adaptable, which are important benefits. Industrial biotechnology is expanding and changing rapidly. As a result, educational materials lose their freshness, if not their relevance. When the hard foundational work of creating a MOOC is done, software and screencasts could replace or upgrade course content in a matter of minutes.

Specialist training facilities

For early-career scientists, gaining access to bio-based production experience is difficult because universities do not normally have such facilities. Ireland is an exception with its National Institutes model, which includes a dedicated facility for training in bioprocessing (the National Institute for Bioprocessing Research and Training, NIBRT). For a relatively small country, Ireland has a large pharmaceuticals sector. NIBRT provides a "one stop shop" for bioprocessing training requirements (NIBRT, n.d.). The institute builds tailored solutions for clients, ranging from operator through to senior management training. Further, it delivers training in a realistic environment with simulated good manufacturing practices (GMPs). This type of environment, not typically found in universities, is more appropriate to train industry professionals. Equally, undergraduate and graduate programmes could use such a facility to expose students to industry working conditions.

A role for intermediate research organisations and laboratories

Intermediate research organisations (IROs) can enable work in selected fields without the conflicting pressures of publishing and teaching explicit in academic research (Gauvreau, Winickoff and Philp, 2018). The concept seems enshrined in the UK Catapult model (Catapult, n.d.), a concept that could have been tailor-made for industrial biotechnology. Further, such a model has great potential to fill skill gaps (more on the apprentice, hands-on model rather than on the academic student model).

Such a model can work for PhD students as well. For example, the RIKEN Junior Research Associate programme in Japan provides part-time positions for young researchers enrolled in Japanese university PhD programmes (RIKEN, n.d.). This enables PhD students to carry out research alongside RIKEN scientists and also strengthens relationships between RIKEN and universities in Japan.

Business management education and training for the industrial biotechnology industry

One solution to a shortage of experienced managers in the biotechnology industry has been to create a specific stream for biotechnology within the normally generic MBA programme (OECD, 2005). Theories of business administration have their roots in commerce, which has in the past been focused on non-technological issues (Lambert, 2004). Therefore, the typical MBA programme is not particularly well-suited to industrial biotechnology business management. Given the pressures on small companies active in industrial biotechnology, much shorter courses that focus on specific skills gaps may be more appropriate.

Given the potential impact of industrial biotechnology on the chemicals industry, a European five-day mini-MBA[1] tailored for mid-level chemical industry managers is pertinent. These managers' roles are being impacted by the rapidly evolving trends of globalisation; registration, evaluation and authorisation of chemicals; green chemistry; waste reduction; sustainability; and operational efficiency. All are also directly relevant to the emerging bio-based industry.

A four-day synthetic biology-specific MBA has also been developed (SynbiCITE, n.d.). It covers the main strategies required to establish, build and manage a biotechnology company built around synthetic biology. It has focused on the early stages of setting up a company, getting funding and understanding the wider reaches of intellectual property.

Training technicians: Providing the bio-manufacturing workforce

Technicians are workforce employees, not researchers. As they are responsible for day-to-day work in bio-manufacturing, technicians will be required in higher numbers than researchers and need a broader range of skills. Industrial biotechnology should be part of their training, not all of it. Some foreseeable functions will be routine maintenance of metabolically engineered strains; embedding synthetic biology with GMP guidance; regulatory and compliance training e.g. bio-banking, transportation of live biologicals and document management; standard operating procedures to deal with accidental spills and releases.

They should also be trained in matters such as scale-up, knowledge of packaging and labelling protocols (Wallman et al., 2013). Scale-up is a massive technical barrier in the bio-based industry, especially at the scale of transportation fuels (Westfall and Gardner, 2011), stretching the skills of both strain and fermentation engineers.

Manufacturing does not fit well into normal boundaries of university degree programmes. As a result, it is often marginalised (Glaser, 2013). An approach that creates a vocational workforce locally and separately from the universities – in technical and community colleges, for example – would take pressure off the universities. It would also create more jobs and investment in local or community colleges. This aligns well with thinking that envisages creation of biorefineries and bioeconomy clusters in rural environments as a means of rural regeneration.

The recently established Industrial Biotechnology Innovation Centre in Scotland has developed a range of educational programmes with its collaborative partners to meet the need of the biotechnology industry (IBioIC, n.d.). Jointly with the Forth Valley College, the Higher National Diploma (HND) is specifically designed to create a cadre of technical staff. The newly developed HND involves the study of three crucial disciplines: biology, chemistry and engineering, on either a full-time or part-time basis.

Given national and international plans for biotechnology education, it would desirable to harmonise and standardise qualifications in bio-manufacturing, and probably even essential. Again, this is not necessarily what universities aim to achieve. It is best done close to manufacturing to allow efficient cross-fertilisation between training institutions and industry.

Conclusions

Industrial biotechnology and synthetic biology training requires a paradigm shift in how education is structured. Programmes are needed that encourage creativity and exploration, while harnessing the truly unique inter-disciplinary nature of the field and harvesting the different forms of training highlighted above. To keep pace in a changing world, beyond the traditional debate of depth versus breadth in education, one of the answers lies in training for adaptability and dynamism. Pioneering universities answering this challenge are, and will be, training the next generation of creative and co-operative knowledge and venture builders. These graduates will be able to update and productively use their knowledge to drive innovation. The gradual shift to biomass from crude oil and natural gas as the raw material for production will present a plethora of technical difficulties. It will demand the ability to use knowledge co-operatively to create the factories and products of the future. In response, the shift calls for equally innovative education and bold reforms.

Note

1. These courses do not allow graduates to use the initials "MBA" after their names.

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Glossary

Advanced biofuels. Usually referred to as produced from lignocellulosic sources, these biofuels are produced through the application of advanced conversion processes to crops and novel feedstocks such as algae.

Advanced energy manufacturing tax credit. A tax credit awarded to firms for qualifying investments in renewable and advanced energy projects to support new, expanded or re-equipped domestic manufacturing facilities. For example, the Section 48C tax credit of the American Reinvestment and Recovery Act of 2009 (ARRA) is equal to 30% of the basis of qualifying investments used to manufacture property that will reduce greenhouse gas emissions or air pollutants.

Agenda 2030 for Sustainable Development. The Heads of State and Government and High Representatives met at the United Nations Headquarters in New York from 25 to 27 September 2015 and decided on new global Sustainable Development Goals (SDGs). The 17 SDGs and 169 targets announced are far-reaching in their scale and ambition – this is the "new universal Agenda".

Agricultural residue. Agricultural crop residues are the plant parts, primarily stalks and leaves, not removed from the fields with the primary food or fibre product. Examples include corn stover (stalks, leaves, husks and cobs), wheat straw and rice straw. It can also include other agricultural wastes, including slurry and manure.

Algal lipid biorefinery. Component separation in primary refining results in algal lipids and algal biomass. They generally refer to microalgae, which are often single-celled organisms. Having been grown in a reactor under conditions that allow accumulation of lipids, the lipids are then extracted. The product is an algal oil rich in triglycerides, but also in higher-value materials such as carotenoids and phytosterols. Triglycerides form the basis of biodiesels and are also a potential raw material for the chemical industry.

Aliphatic. Relating to organic compounds whose carbon atoms are linked in open chains, either straight or branched, rather than containing a benzene ring. Alkanes, alkenes and alkynes are aliphatic compounds. They are important molecules in petrochemistry. The alkanes are significant components of liquid transport fuels. The short-chain alkenes, such as ethylene and propylene, are at the heart of the petrochemicals industry.

Anaerobic digestion. Degradation of organic matter by microbes that produces a gas comprised mostly of methane and carbon dioxide in the absence of oxygen.

Aromatic. The term was coined simply because many of the aromatic compounds have a sweet or pleasant odour. Aromatic hydrocarbons contain six carbon atoms in a ring structure known as a benzene ring, after the simplest one, benzene. Aromatic compounds have many uses. The aromatic ring can be found in rubbers, lubricants, dyes, detergents, drugs, explosives and pesticides, among others. Apart from their widespread utility, many are toxic to very toxic, and some are known to cause cancer. Bio-based versions are difficult to manufacture.

B20. A mixture of 20% biodiesel and 80% petroleum diesel based on volume.

Bagasse. Residue remaining after extracting a sugar-containing juice from plants like sugar cane.

Barrel (of oil). A liquid measure equal to 42 US gallons (35 Imperial gallons or 159 litres); about 7.2 barrels are equivalent to 1 tonne of oil (metric).

Benzene. A six-sided structure with three alternating double bonds. It is a known carcinogen that is an aromatic component of petrol.

Bio-based chemicals tax credit. The US Renewable Chemicals Act of 2015 would create a 15 cent-per-pound production tax credit for eligible renewable chemicals manufactured from biomass feedstock. Alternatively, the bill would allow producers to take a 30% investment tax credit for qualified investments for new renewable chemical production facilities in lieu of the production tax credit. The Qualifying Renewable Chemical Production Tax Credit Act of 2012 would provide renewable chemical and bio-based products access to tax credits that are available to other industries.

Bio-based content. The amount of bio-based carbon in the material or product as a percent of weight (mass) of the total organic carbon in the material. This is an important indicator of renewability, but not necessarily of sustainability. Bio-based products need not be composed entirely of bio-based carbon. The emerging bio-based manufacturing industry produces large quantities of products that contain mixtures of bio-based and fossil-derived materials, e.g. first-generation bio-polyethylene terephthalate (bio-PET, the material commonly used to make drink bottles).

Bio-based product. A product made partially or entirely from substances derived from living matter. It may include common materials such as wood and leather, but typically means modern materials that have undergone more extensive processing. Bioproducts or bio-based products include materials, chemicals and energy derived from renewable biological resources. Bio-based materials are often, but not necessarily, biodegradable. The term is typically applied only to materials containing carbon.

Biocoal. This is a solid fuel made from biomass by heating it in an inert atmosphere. The result is either charcoal, or if the process temperature is mild, a product called "torrefied wood". Charcoal and torrefied wood can be called by the common name biocoal. Compared to untreated biomass, biocoal has several advantages. It has high energy content, uniform properties and low moisture content.

Biodegradable. Capable of being decomposed by biological agents, especially bacteria and fungi. Biodegradable has proven a controversial term as it does not necessarily mean biodegradation to its mineral components, despite the implications of marketing. Partial biodegradation can, in fact, result in a stable intermediate compound that is more toxic than the original molecule. Mineralisation means the ultimate conversion of the material or compound to its mineral components (CO_2 and H_2O under aerobic conditions). Biodegradability usually refers to the testing regime under which a compound or material is judged to be biodegradable or not.

Biodiesel. Biodiesel is an alternative to fossil diesel fuel in transport. It is similar in composition, but can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. A biodiesel of the future will be derived from algae. Biodiesel can be used alone, or blended with petro-diesel in any proportions. Indeed, many renewable energy policies depend on blending. Biodiesel blends can also be used as heating oil.

Biodiversity. The variety of all life on Earth, including all species of animals and plants, and the natural systems that support them. There are ongoing studies on the links between climate change and biodiversity from at least two perspectives: impacts of climate change and climate policy on biodiversity and ecosystem services, and the role of biodiversity and ecosystem services in climate change mitigation and adaptation.

Biocatalyst. Usually refers to enzymes and microbes, but it can include other catalysts that are living or that were extracted from living organisms, such as plant or animal tissue cultures, algae, fungi or other whole organisms.

Biocrude. A crude oil similar to petroleum that can be produced from biomass under high pressure and temperature.

Biodiesel. Conventionally defined as a biofuel produced through transesterification, a process in which organically-derived oils are combined with alcohol (ethanol or methanol) in the presence of a catalyst to form ethyl or methyl ester. The biomass-derived ethyl or methyl esters can be blended with conventional diesel fuel or used as a neat fuel (100% biodiesel). Biodiesel can be made from soybean or rapeseed oils, animal fats, waste vegetable oils or microalgae oils. (Note: Biodiesel can in certain circumstances include ethanol-blended diesel. This is an evolving definition.)

Bioeconomy. Since a landmark OECD publication, bioeconomy definitions have varied, and as yet there is no consensus. From a broad economic perspective as envisaged by the OECD, the bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products and processes. However, it has come to include agriculture, forestry, pulp and paper, and other sectors. Some countries include health in the definition. Therefore, estimates of the size of the bioeconomy vary enormously.

Bioenergy. Energy generated by combusting solid, liquid or gas fuels made from biomass feedstocks, which may or may not have undergone some form of conversion process. Organic matter may either be used directly as a fuel processed into liquids and gases, or be a residual of processing and conversion.

Bioethanol. Bioethanol is the principal fuel used as a petrol substitute for road transport vehicles, generally produced from crops such as sugar cane, corn and wheat. It can be made from virtually any biomass source (grass, wood, biodegradable elements of municipal solid waste), but the technologies for doing so are still under development.

Biofuel. A fuel produced from biomass feedstocks. Strictly speaking, fossil fuels fit this definition, but biofuels are distinguished from fossil fuels in that they are produced from renewable biomass, i.e. crops that can be harvested for refinement to biofuels, and replanted and reharvested on a continuing basis.

Biofuel intermediate. A biomass-based feedstock that serves as a petroleum replacement in downstream refining, (i.e. sugars, intermediate chemical building blocks, bio-oils and gaseous mixtures). Algal biofuel intermediates include extracted lipids, lipid-extracted biomass or bio-oil resulting from hydrothermal liquefaction.

Biofuels sustainability criteria. In the European Union, to be considered sustainable (and therefore qualify for government support), biofuels must achieve greenhouse gas savings of at least 35% in comparison to fossil fuels. This savings requirement rises to 50% in 2017. In 2018, it rises again to 60%, but only for new production plants. All life cycle emissions are taken into account when calculating greenhouse gas savings. This includes emissions from cultivation, processing and transport. In addition, biofuels cannot be grown in areas converted from land with previously high carbon stock such as wetlands or forests; and they cannot be produced from raw materials obtained from land with high biodiversity such as primary forests or highly biodiverse grasslands.

Biogas. Biogas typically refers to a mixture of different gases produced by the breakdown of organic matter in the absence of oxygen. Biogas can be produced from raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste or food waste. It is typically depicted as a mixture of methane and carbon dioxide with traces of many other gases possible in some sources e.g. landfill gas.

Biogas biorefining. Here there is no separate component separation in primary refining. The organic materials present in the feedstock are anaerobically decomposed in a complex microbiological process to biogas, comprised mainly of methane and CO_2. The gas is flammable and can be burned to produce heat and electricity. In wastewater treatment plants, this is traditionally called anaerobic digestion, and can in many cases meet the electricity needs of the entire plant.

Biomass. This is the biological raw material used to make fuels or other bio-based products. It includes solid biomass such as wood, plant and animal products, gases and liquids derived from biomass, and the biodegradable components of industrial and municipal wastes. Processing and conversion derivatives of organic matter are also biomass.

Biomass potential. Biomass potential refers to the amount of biomass that can be grown. In the modern policy setting, this will refer to the sustainable biomass potential. Several biomass potential studies have been done in the last few decades. Their approaches have been very different and their results difficult to compare and interpret. They can be done at local, regional, national levels or above. Without standardised criteria for measuring biomass potential, future estimates will continue to be uncomparable and variable.

Biomass sustainability. The meaning of biomass sustainability depends on what is meant by sustainability. The latter has come to be associated with safeguarding the future by not taking out more from the planet than necessary. This responds to the habit of rapid population growth and development being accompanied by a "throw-way" mentality when resources are finite. Therefore, it calls for using renewable resources and higher levels of recycling.

Bioplastic. There is no universally agreed definition of a bioplastic. Bioplastics were first introduced as biodegradable plastics for use in simple packaging applications. The bio-based plastics that are now increasing in the market are not necessarily biodegradable, but they contain carbon that is partially or entirely derived from renewable biomass.

Bio-principled cities. The integration of biological principles into urban planning and city life. It calls for higher levels of self-sufficiency of cities and more recycling to reduce waste and close energy and material loops.

Blending tax credit. Biofuels blenders are eligible for an income tax credit per litre or gallon. For example, under the US Biodiesel Production and Blending Tax Credit, qualified biodiesel producers or blenders are eligible for an income tax credit of USD 1.00 per gallon of pure biodiesel (B100) or renewable diesel produced or used in the blending process. For the purpose of this credit, biodiesel must meet ASTM specification D6751, and renewable diesel is defined as a "renewable, biodegradable, non-ester combustible liquid derived from biomass resources that meets ASTM specification D975". The blending tax credit has been criticised for being accessible to foreign biofuels; a producer's credit would support domestic production more. On the other hand, proponents of the blender's credit say that a producer-only credit increases profits for a limited number of producers, while reducing the overall availability of fuels.

Business ecosystem/ecology. A system-level view of the relationships and interdependencies evident in organisations, markets or industries, including their components, actors, resources and stakeholders. Inspired from nature, this is a similar approach to understanding biological ecosystems in their fullest sense.

By-products. These occur as a result of primary- and/or secondary refining, and are used to supply process energy or, where applicable and in compliance with statutory requirements, are further processed into food or feed.

Cap and trade. A cap is placed on the total amount of allowable emissions, it is distributed among the total number of polluters and a marketplace is created where owners of the permits can trade with each other. The intention is to incentivise a reduction in emissions and penalise those who fail to comply.

Capital cost. The total investment needed to complete a project and bring it to an operable status. The cost of construction of a new plant. The expenditures for the purchase or acquisition of existing facilities.

Carbon capture and storage (CCS). This technology involves capturing CO_2, transporting it and storing it in secure spaces such as geological formations, including old oil and gas fields, and aquifers under the seabed.

Carbon dioxide equivalents (CO_2e). The internationally recognised way of expressing the amount of global warming of a particular greenhouse gas in terms of the amount of CO_2 required to achieve the same warming effect over 100 years.

Carbon footprint. The total emissions of greenhouse gases (in carbon equivalents) from whichever source is being measured – be it at an individual, organisation or product level.

Carbon-neutral. Carbon neutrality makes or results in no net release of carbon dioxide into the atmosphere, especially as a result of carbon offsetting.

Carbon offsetting. The process of reducing greenhouse gas emissions by purchasing credits from others through emissions reductions projects or carbon trading schemes. The term often refers to voluntary acts, arranged by a commercial carbon offset provider.

Carbon price and carbon tax. A carbon price is the amount that must be paid for the right to emit one tonne of CO_2 into the atmosphere. Carbon pricing usually takes the form either of a carbon tax or a requirement to purchase permits to emit, generally known as cap and trade. Carbon pricing has proven extremely controversial politically. As a consequence of not being priced, there is no market mechanism responsive to the costs of CO_2 emitted. Classically, emissions should be charged at a price equal to the monetary value of the damage caused by the emissions. This should result in the economically optimal (efficient) amount of CO_2 emissions. However, the price of the damage has remained elusive.

Carbon trading. Any trading system designed to offset carbon emissions from one activity (such as burning fossil fuels in manufacturing, driving or flying) with another (such as installing more efficient technologies, planting carbon-reducing plants or establishing contracts with others not to partake in carbon-releasing activities). When activities that reduce or capture carbon are paired successfully with those that produce it, these are said to be carbon neutral or climate neutral.

Cascading use. This usually refers to the cascading use of biomass. The theory goes that the highest value products, generally in the lowest volumes, are extracted from biomass first. Then the same biomass cascades towards the lowest value products, often the highest-volume materials. Recycling is applied as often as possible before the biomass and its products reach the end of their life, perhaps by burning to generate electricity. In this manner, the maximum value is theoretically extracted from the original biomass. It has been estimated that cascading can lead to an almost 30% reduction in European greenhouse gas emissions by 2030 compared with 2010.

Certification schemes and labels. In certification schemes, independent organisations test materials or products. If results are satisfactory, the organisations issue a certificate stating that the material or product meets the requirements (prescriptions) of a particular standard. Certification of bio-based products informs users about the nature of the material or product. Certification is often accompanied by a label that may be placed on certified materials and products.

Circular economy. This is strongly associated with recycling. It refers to closed loops of energy and material use in that the residues and by-products of one process can be used in another. The ultimate goal of a circular economy would be “zero waste”. A strong relationship to cascading use will be evident.

Clean production. Manufacturing processes designed to minimise environmental impact by using the minimum amount of energy and raw materials possible and producing limited waste or emissions.

Clear cutting. A process where all trees in a selected area are felled in a logging operation. This can be extremely destructive to the environment, while being the most cost-effective means known to harvest high yields of timber rapidly.

Climate change. Climate change has come to be associated with global warming as a result of human activities since the Industrial Revolution, but it is also caused by factors such as oceanic processes, variations in solar radiation, plate tectonics and volcanic eruptions. The term is now almost universally used to describe impacts resulting from human activity.

Combined Heat and Power (CHP). A system in which the heat associated with electricity generation is used for space heating or process heat. It considerably increases the overall efficiency of the fuel used in the process. Energy generated by the incineration of waste at local combined heat and power facilities can support district heating schemes.

Composting. In the context of sustainability this refers to a regulated industrial-scale process for converting decomposable organic materials into useful stable products through biochemical processes. Industrial-scale composting through in-vessel composting, aerated static pile composting and anaerobic digestion is now used in most Western countries and is often legally mandated. Composting is one of the very few ways to revitalise soil in which the phosphorus is depleted.

Conventional biofuels. These are transport biofuels typically derived from crops and waste using current conversion processes. Examples include bioethanol from sugar cane and biodiesel from oilseed rape and used cooking oil. These are also known as first-generation biofuels.

CO_2 economy. A CO_2 economy encompasses both carbon capture and storage (CCS) and carbon capture and use (CCU). For example, hot, pressurised CO_2 can be used not only for generating power, but also for higher-value, carbon-negative products, such as synthetic gasoline and diesel fuel. This ushers in an era of possibilities: clean, reliable baseload energy; a cost-effective means to capture greenhouse gases; and the affiliated production of potent carbon-negative, fossil fuel substitutes. But the CO_2 economy can also be associated with a low-carbon economy (due to the renewable and recyclable elements of the theory).

Cradle-to-cradle. A design protocol that advocates the elimination of waste by recycling a material or product into a new or similar product at the end of its intended life, rather than disposing of it.

Cradle-to-gate. An assessment of a partial product life cycle from manufacture ("cradle") to the factory gate i.e. before it is transported to the user or consumer. The use phase and disposal phase of the product are usually omitted. Cradle-to-gate assessments are sometimes the basis for environmental product declarations. They are of greatest use to manufacturers, who cannot foresee what customers will do with their products.

Cradle-to-grave. A manufacturing model that describes the process of disposing of a material or product via a recognised route, such as landfill or incineration, at the end of its presumed useful life.

Dedicated energy crops. These are crops grown to be used for energy generation. Examples include fast-growing trees (such as short rotation coppice willow) and grasses with a high lignocellulosic content (such as *Miscanthus*).

Deforestation. This is the clearing of the planet's forests on a massive scale, often resulting in damage to the quality of the land, and reducing the capacity of the planet to absorb CO_2. An estimated 13 million hectares of forests were lost each year between 2000 and 2010 due to deforestation.

Direct land-use change (DLUC). The conversion of land from one use to another, e.g. from unmanaged forest to cropland, or from one crop type to another. The tillage of unmanaged land exposes large amounts of soil organic carbon to the atmosphere and produces large amounts of CO_2. It can take a long time to pay back this CO_2 debt.

Drop-in fuel. A substitute for conventional fuel that is completely interchangeable and compatible with conventional fuel. A drop-in fuel does not require adaptation of the engine, fuel system or the fuel distribution network and can be used "as is" in available engines in pure form and/or blended in any amount with other fuels.

Eco-label. An environmental label or declaration that provides information about a product or service in terms of its overall environmental character, a specific environmental aspect or number of environmental aspects. The information can be used to influence or inform purchasing decisions. Eco-labels may take the form of a statement, symbol or graphic and be found, in part, on products or packaging and in product literature or advertising.

E-10. A mixture of 10% ethanol and 90% petrol based on volume. In the United States, E-10 is the most commonly found mixture of ethanol and petrol.

E-85. Typically refers to an ethanol fuel blend of 85% denatured ethanol fuel and 15% petrol or other hydrocarbon by volume.

Emission. The release of any gas, particle or vapour into the environment from a commercial, industrial or residential source, including smokestacks, chimneys and motor vehicles.

Emissions trading. This refers to the trading of permits that allow emissions of set amounts of greenhouse gases. It is therefore a market mechanism for controlling pollution. By creating tradable pollution permits, it attempts to add the profit motive as an incentive for good performance, unlike traditional environmental regulation based solely on the threat of penalties.

End-of-life options. This refers to the step in the life of a chemical or material after its primary intended purpose has been fulfilled. The chemical or material may then be used for another purpose. Often it becomes a waste product. Here the options typically are discarding to landfill, incineration (with or without energy capture and electricity production), composting (for biodegradable wastes) and recycling for further use.

Energy crops. Crops grown specifically for their fuel value. These crops may include food crops such as corn and sugarcane, and non-food crops such as poplar trees and switchgrass.

Energy density. In terms of fuels, energy density means the amount of energy stored in a given liquid, per unit volume (litre or gallon, normally). Ethanol has a higher energy density than methanol, meaning a vehicle can be driven farther on a litre of ethanol than a litre of methanol. Biomass is also described as being of low energy density, making it inefficient to transport over long distances.

Energy intensity. There are two meanings in common use. First, it can be a measure of the energy efficiency of a national economy, calculated as units of energy per unit of gross domestic product. Second, it can be the entire amount of energy required to produce a product as a ratio of that product.

Energy recovery. This is obtaining energy from waste. It is accomplished through a variety of processes, and is also known as "waste-to-energy". Traditionally, this meant burning waste products, but now gasification and anaerobic digestion are also playing a role.

Energy security. At its core, energy security is the concept of physical security (avoiding involuntary interruptions of supply). It can include elements of price security (e.g. avoidance of excessive price volatility). In the context of sustainability and affordability and as a result of volatility of fossil fuel prices, many countries seek to improve energy security through diversification of supply, e.g. biofuel production, offshore and onshore wind energy, solar power.

Enzymatic hydrolysis. Use of an enzyme to promote the conversion, by reaction with water, of a complex substance into two or more smaller molecules.

Enzyme. One of various proteins that act as catalysts for a single reaction, converting a specific set of reactants into specific products.

Eutrophication. The process by which a body of water becomes enriched in dissolved nutrients (such as phosphates) that stimulate the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen that can lead to fish kills and loss of other life forms.

Externality. A cost or benefit not accounted for in the price of goods or services. Often refers to the cost of pollution and other environmental impacts.

Feed-in tariff. A feed-in tariff (FIT), or advanced renewable tariff or renewable energy payments is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each technology. Producers may be generating companies of any size, all the way down to the individual home. It is effectively a scheme that pays people for creating their own green or renewable electricity. For governments, FITs help meet national production targets on renewable energy and therefore for greenhouse gas emissions reductions.

Feedstocks. Any material converted to another form or product, or the starting material for a process. It includes crops or products that can be used to produce bioenergy or bio-based products. Examples are wood, switchgrass, waste paper, agricultural residues, corn and soybeans.

Fermentation. The use of microorganisms (e.g. yeasts, bacteria) to break down organic substances to create other organic substances. The classic fermentation is the anaerobic conversion of sugars into ethanol by the yeast *Saccharomyces cerevisiae*. In strict scientific terms, fermentation is an anaerobic process, but in practice the term is also used for aerobic biological conversion processes.

Fischer-Tropsch. The Fischer-Tropsch process is a set of chemical reactions that converts a mixture of carbon monoxide gas and hydrogen gas into liquid hydrocarbons (fossil fuels like gasoline or kerosene).

Flex-fuel vehicle (FFV). A vehicle that operates with more than one fuel or fuel blend. For example, the Ford Model T, produced from 1908 to 1927, was fitted with a carburettor with adjustable jetting, allowing use of petrol or ethanol, or a combination of both. FFVs have been designed for modern use with petrol or ethanol, and blends thereof, in many countries as a means of reducing emissions, most notably in Brazil and Sweden.

Food security. Food security refers to the availability of food. In the bioenergy context, it relates to the food vs. fuel debate about diverting farmland from food crops to bioenergy feedstocks and the perception that this leads to higher food prices and decreased food supply worldwide. The origins of the recent food price spikes, however, are complex and include other issues such as the price of fossil fuels.

Forestry and forest residues. These forest sector by-products include residues from thinning and logging (e.g. treetops, limbs) and secondary residues such as sawdust and bark from wood processing. Forestry and forest residues also include dead wood from natural disturbances, such as fires, biomass grown in forests that is not required for timber production, and biomass from dedicated plantations, e.g. short- and long-rotation forestry.

Fossil fuel. Coal, oil and gas are called fossil fuels because they were formed from the fossil remains of plants and animals millions of years ago. As fuels, they offer high energy density, but making use of that energy requires burning the fuel and the oxidation of the carbon to CO_2 and H_2O. Unless they are captured and stored, these combustion products are released and return carbon sequestered millions of years ago to the atmosphere.

Fossil fuel subsidies. These are any government actions that lower the cost of fossil fuel energy, that raise the price received by energy producers or lower the price paid by energy consumers. There are a lot of activities under this simple definition – tax breaks and giveaways, but also loans at favourable rates, price controls, purchase requirements and more. The global value of these subsidies is vast, by most calculations of the order of half a trillion USD per annum. They therefore have the global effect of distorting the fossil fuel markets. For example, the price of petrol in a Western European country can easily be more than one hundred times the price in Venezuela at a given time.

Fuel cell. A device that converts the energy of a fuel directly to electricity and heat, without combustion.

Gasification. The process that converts organic or fossil fuel-based carbonaceous materials into CO, H_2 and CO_2, and possibly hydrocarbons such as CH_4. This is achieved by reacting the material at high temperatures without combustion, with a controlled amount of oxygen and/or steam. It can therefore be viewed as a “partial oxidation” process.

Genetically modified. An organism is genetically modified if it contains genetic material that has been artificially altered to produce a desired characteristic. The term has become extremely political and societally divisive, leading to multiple interpretations of its meaning. The greatest controversy is with food. Genetically modified (GM) foods are foods derived from organisms whose genetic material (DNA) has been modified in a way that does not occur naturally, e.g. through the introduction of a gene from a different organism.

Genome. A genome is the complete set of DNA, including all of the genes, of an organism. Each genome contains all of the information needed to build and maintain that organism. In humans, a copy of the entire genome – more than 3 billion DNA base pairs – is contained in all cells that have a nucleus.

Genomics. Now a rather broad term, it is the branch of molecular biology concerned with the structure, function, evolution and mapping of genomes.

Global warming. The gradual increase in the overall temperature of the Earth's atmosphere generally attributed to the greenhouse effect caused by increased levels of carbon dioxide, CFCs and other pollutants. By overwhelming scientific consensus, global warming is caused by human activity.

Green bank. A green bank is a public or quasi-public financing institution that provides low-cost, long-term financing support to clean, low-carbon projects by leveraging public funds using various financial mechanisms to attract private investment. In this way, each public dollar supports multiple dollars of private investment. An early example is the UK Green Investment Bank. Typical projects could include offshore and onshore renewable energy, offshore wind, solar, energy efficiency, waste and bioenergy.

Green chemistry. The design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Hazardous now has come to include greenhouse gases, in particular CO_2. There is now an emphasis on the link between green chemistry and climate change/global warming.

Green engineering. Engineering with environmentally conscious attitudes, values and principles, combined with science, technology and engineering practice, all directed towards improving local and global environmental quality.

Green growth. This term describes a path of economic growth that uses natural resources in a manner that is sustainable. It is used globally to provide an alternative concept to typical industrial economic growth. A green growth strategy would bring together the three pillars of sustainable development (economic, environmental and social), and incorporate technological and development aspects into a comprehensive framework.

Greenhouse effect. The greenhouse effect is the process by which radiation from the atmosphere of the planet warms its surface to a temperature above what it would be without its atmosphere.

Greenhouse gas (GHG). Any atmospheric gas (either natural or of human origin) that absorbs thermal (infrared) radiation emitted by the Earth's surface. This traps heat in the atmosphere and keeps the surface at a warmer temperature than would otherwise occur. The primary greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone.

Greenwashing. A term merging the concepts of "green" (environmentally sound) and "whitewashing" (to conceal or gloss over wrongdoing). Greenwashing is any form of marketing or public relations that links a corporate, political, religious or non-profit organisation to a positive association with environmental issues for an unsustainable product, service or practice.

Gross domestic product (GDP). A measure of economic production (and often standard of living) of a country. GDP calculates a nation's total economic output of products and services. The GDP is problematic as a sustainability indicator because it considers the amount of money spent in a country in isolation, assuming more money spent means a healthier economy.

Gross national product (GNP). The total value of newly produced products and services produced in a year by a country's companies (including profits from capital held abroad). Transactions in existing goods, such as second-hand cars, are not included, as these do not involve the production of new goods.

Hydrocarbon. A compound of hydrogen and carbon, such as any of those that are the chief components of petroleum and natural gas.

Hydrogenation. This means to treat with hydrogen. It is a chemical reaction between molecular hydrogen (H_2) and another compound or element, usually in the presence of a catalyst. The process is commonly employed to reduce or saturate organic compounds. Hydrogenation is becoming an important tool in the efficient conversion of biomass to value-added products.

Hydrogen economy. The term refers to the vision of using hydrogen as a low-carbon energy source – replacing, for example, petrol as a transport fuel or natural gas as a heating fuel. However, its "green" credentials are questioned if the hydrogen is generated by steam reformation of hydrocarbons. Other means of generation, such as water electrolysis, require large energy inputs. Bio-based hydrogen to date suffers from poor production and therefore applications at large scale are still evanescent.

Hydrolysis. In relation to biorefining, the hydrolysis of biomass is usually taken to mean the hydrolysis of cellulose present in biomass to produce sugars and other organic compounds that can be subsequently fermented. In chemistry, it literally means the chemical breakdown of a compound due to reaction with water.

Hydrothermal. Hydrothermal processing of biomass is similar to torrefaction, but uses milder treatment conditions. Hydrothermally processed biomass is commonly referred to as "biocoal".

Incineration. Incineration of waste materials converts the waste into ash, flue gas and heat. The flue gases should be cleaned of gaseous and particulate pollutants before they are dispersed into the atmosphere. In some cases, the heat generated by incineration can be used to generate electric power. Incinerators reduce the solid mass of the waste by 80-85% and the volume by 95-96%. Incineration does not completely replace landfilling, but significantly reduces the volume to be disposed of.

Indirect land-use change (ILUC). Indirect land-use change occurs when land used for an existing activity (e.g. food or timber production) is converted to grow a bioenergy feedstock or when a food crop is used for bioenergy (e.g. diversion of maize for ethanol production). It is assumed that food production is essential and that the lost food production will be diverted elsewhere.

Industrial biotechnology. Industrial or white biotechnology uses enzymes and microorganisms to make bio-based products in sectors such as chemicals, food and feed, detergents, paper and pulp, textiles and bioenergy (such as biofuels or biogas).

Industrial ecology. A field of study and practice that focuses on how industry can be developed or restructured to reduce environmental burdens throughout the product life cycle (extraction, production, use and disposal). In applying this perspective, companies seek to shift industrial processes from open-loop systems that produce waste materials to closed loop systems where wastes become inputs for new processes. Perhaps the best-known example is Kalundborg, Denmark.

Industrial metabolism. The total use of materials and energy throughout an entire industrial process, such as manufacturing. This includes the source, transportation, use, reuse, recycling and disposal of all industrial nutrients (materials), as well as the energy needed at each step.

Irrigation. Irrigation becomes an issue of sustainability because about 70% of fresh water use is for agriculture. Much of this is used for irrigation. Irrigation is the artificial application of water to the land or soil. It is used to assist in the growing of agricultural crops, maintenance of landscapes and revegetation of disturbed soils in dry areas and during periods of inadequate rainfall. Methods vary greatly in their efficiency. One of the drives in plant genomics is to produce crop varieties that are heat- and drought-tolerant to reduce use of water in agriculture, thereby improving water security.

Integrated biorefineries. In the integrated biorefinery model, multiple products are made at the same facility or complex – biofuels, bio-based materials and bioenergy. Often the economics of bio-based chemicals production will be superior to those of biofuels production (this is also the case in petro-production). Integration is widely accepted as the most sustainable form of biorefining for the future.

Kyoto Protocol. Adopted in 1997 as a protocol to the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol placed a legally binding commitment on participating countries to reduce their greenhouse gas emissions by 5% relative to 1990 levels over the period from 1998 to 2012. Gases covered by Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydroflurocarbons (HFCs) and perfluorocarbons (PFCs).

Landfill. In the sustainability context, landfill refers to ground filled in with waste materials; in other contexts, it can refer to rocks. Landfill is the most common organised waste disposal technology. As waste is buried in landfill, the site rapidly becomes anaerobic, with the result that materials that biodegrade produce methane, which can be captured and burned for heat or electricity production. If the methane production is not controlled, it contributes to GHG emissions. Decades of concern over the declining number of suitable sites for landfilling has led to legislation to limit materials that are landfilled.

Life cycle analysis (LCA). This is a numerical technique to assess environmental impacts associated with all the stages of the life of a product, typically from cradle-to-grave (i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. There are several variants of cradle-to-grave in common use.

- Cradle-to-factory gate assesses the product life cycle from resource extraction (cradle) to the factory gate i.e. before it is transported to the consumer. This variant is often favoured by the manufacturer, which does not control the consumer's use and disposal of the product.
- Cradle-to-cradle (also known as open-loop production) is a cradle-to-grave assessment for which recycling is the end-of-life option.
- Well-to-wheel is a specific LCA used for transport fuels and vehicles.

Lifecycle emissions. The emissions generated by a product, system or service over its lifetime.

Lignin. An amorphous polymer related to cellulose that, together with cellulose, forms the cell walls of woody plants and acts as the bonding agent between cells.

Lignocellulosic biorefining. In dry biomass-based lignocellulosic biorefining, the component separation in the primary refining produces the lignocellulosic components cellulose, hemicelluloses and lignin, extremely common components of plant and woody materials. The feedstocks are various e.g. straw, forestry trimmings, other agricultural residues and dedicated energy crops.

Lignocellulosic feedstock. Woody feedstocks with significant cellulose and hemicellulose content. Advanced conversion processes are required to break down the cellulose and hemicellulose for conversion to liquid biofuels or bio-based products. The biorefining of these feedstocks involves a high cost.

Loan guarantee. A loan guarantee in finance is a promise by one party (the guarantor) to assume the debt obligation of a borrower if that borrower defaults. A guarantee can be limited or unlimited, making the guarantor liable for only a portion or all of the debt. This has become a major finance instrument for the construction of high-risk and flagship (first-of-kind) biorefineries.

Managed forests. In a managed forest, trees are replanted as they are felled. Wood products that come from well-managed forests offer the most benefits in terms of combating climate change. Well-managed woodlands also generally store more carbon than stands that are not harvested.

Market failure. A market's inability to create maximum efficiency by not properly providing goods or services to consumers, not efficiently organising production or not serving the public interest. The term does not refer to the collapse or demise of a market.

Materials audit. The process of investigating the costs and effects of materials used in manufacturing in order to determine more efficient, less costly, less toxic (or dangerous) and more sustainable options.

Metabolic engineering. The use of genetic engineering to modify the metabolism of an organism. It can involve the optimisation of existing biochemical pathways or the introduction of pathway components, most commonly in bacteria, yeast or plants, with the goal of high-yield production of specific molecules for medicine or biotechnology. It has many applications in bio-production of chemicals, plastics, textiles and other materials.

Metabolomics. The comprehensive analysis of all low-molecular-weight primary and secondary metabolites present in and around cells growing under defined physiological conditions. It is emerging as a rapidly developing field of research with the promise to speed up the functional analysis of genes of unknown function. The metabolome is the final downstream product of gene transcription. Additionally, as the furthest downstream product, the metabolome is closest to the phenotype of the biological system being studied.

Metagenomics. The application of modern genomics technologies to microbial communities in their natural environments, bypassing the need for culturing. The vast majority of bacterial life, for example, remains unculturable using available methods. For almost the entire history of microbiology as a discipline, perhaps 90-99% of the diversity of bacteria has been a complete mystery.

Municipal solid waste (MSW). Any organic matter, including sewage, industrial and commercial wastes, from municipal waste collection systems. Municipal waste does not include agricultural and wood wastes or residues.

Net present value (NPV). The value, in the present, of an investment or financial transaction that will pay off in the future, minus the cost of the investment up until the time of that pay-off. NPV represents the profit or loss, in present worth, of future transactions so they are comparable against other investments. Large, time-consuming construction projects are managed on this basis e.g. developing an oilfield.

Non-renewable energy. Energy derived from sources that cannot be replenished in a short period of time relative to a human life span. Non-renewable sources of energy are typically divided into two types: fossil fuels and nuclear fuels. Fossil fuels include oil, natural gas and coal. Nuclear involves uranium.

Open-loop recycling. The conversion of material from one or more products into a new product, involving a change in the inherent properties of the material itself e.g. recycling plastic bottles into plastic drainage pipes. This is also referred to as downcycling or reprocessing.

Operating cost. The expenses related to the operation of a business, or to the operation of a device, component, piece of equipment or facility. They are the cost of resources used by an organisation just to maintain its existence.

Organic compound. Compound containing carbon chemically bound to hydrogen. Often contains other elements (particularly O, N, halogens or S).

Oxygenate. A compound that contains oxygen in its molecular structure. Ethanol and biodiesel act as oxygenates when they are blended with conventional fuels. Oxygenated fuel improves combustion efficiency and reduces tailpipe emissions of CO.

Paris Agreement, 2015. The Paris Agreement is an agreement within the framework of the United Nations Framework Convention on Climate Change (UNFCCC) governing greenhouse gas emissions mitigation, adaptation and finance from 2020. The agreement was negotiated during the 21st Conference of the Parties of the UNFCCC in Paris and adopted by consensus on 12 December 2015, but has not entered into force. In the 12-page Agreement, the members promised to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2 degrees C".

Peak oil. A controversial concept, peak oil is the hypothetical point in time when the global production of oil reaches its maximum rate, after which production will gradually decline (some models envisage precipitous decline). It has political dimensions that pertain to sustainability as it can be used as an argument for greater deployment of renewable energy and materials production.

Precautionary principle. An approach to determining whether a given process or policy should be pursued or continued based on an analysis of the social, economic or environmental risks associated with that activity. Not all risks are known when a new practice is introduced or a current one is re-examined. The ethical approach in light of implied or expected (but not confirmed) negative impacts is to stop such practices as a precaution until more is known about the impacts.

Pollution prevention. Any activity to reduce or eliminate any number of pollution types or quantities from personal, corporate or governmental activities. These activities seek to create more efficient procedures or practices that reduce pollution or use them in the manufacturing process of some other activity. Many countries have integrated pollution prevention and control into policy. The European Union has the Integrated Pollution Prevention and Control (IPPC) Directive that requires industrial and agricultural activities with a high pollution potential to have a permit. This permit can only be issued if certain environmental conditions are met so that the companies themselves bear responsibility for preventing and reducing any pollution they may cause.

Polymer. A large molecule made by linking smaller molecules (monomers) together.

Polysaccharide. A carbohydrate consisting of a large number of linked simple sugar, or monosaccharide, units. Examples of polysaccharides are cellulose and starch.

Primary refining. This involves the separation of biomass components into intermediates (e.g. cellulose, starch, sugar, vegetable oil, lignin, plant fibres, biogas, synthesis gas), and usually also includes the pre-treatment and conditioning of the biomass. While component separation takes place at the biorefinery, one or more pre-treatment/conditioning processes can also be decentralised as needed.

Production (biofuels) mandate. Under the US Renewable Fuel Standard (RFS), first established in 2005, Congress mandated biofuels use for the United States. The US Energy Independence and Security Act (EISA, 2007) superseded and greatly expanded the biofuels mandate to 36 billion gallons by 2022. This was a substantial biofuels policy as it set minimum usage requirements for various road transport biofuels to guarantee them a market irrespective of their cost.

Proteomics. Proteomics is the large-scale study of proteins, particularly their structures and functions, and the proteome is the entire set of proteins produced or modified by an organism or system. Proteomics lagged behind genomics for a long time due to technical difficulties. However, this has progressed radically in recent years and is now on par with most genomic technologies in throughput and comprehensiveness.

Protein. A long chain of amino acids, folded into a more or less compact structure.

Public-private partnership (PPP). Widely used in science and technology policy, public-private partnership models of different varieties exist. The general idea is that public (taxpayers') money pump-primes greater financial support from the private sector. This signals policy stability from governments and de-risks private investments when the private sector is unwilling to shoulder the risk alone. PPPs are well- suited to the high risk associated with biorefinery projects, especially the integrated biorefineries of the future.

Public procurement. This can be a powerful market-making measure. It involves mass purchasing of commodities by the public sector. Obvious examples might be military procurement of biodiesel, or public procurement of fleet vehicles, such as flex-fuel vehicles for police forces or the post office to encourage the uptake of renewable fuels. PP affects a substantial share of world trade flows. For example, in the European Union this accounts for roughly 18% of GDP.

Pyrolysis. The breaking apart of complex molecules by heating in the absence of oxygen, producing solid, liquid and gaseous fuels.

Recycling. The processing of used waste materials into new products to reduce waste production, reduce the consumption of fresh raw materials, reduce energy usage, reduce air and water pollution and lower greenhouse gas emissions as compared to virgin production. Many materials, such as thermoplastics and glass, are recyclable. Although typically an alternative to landfilling, there is some debate about whether recycling is economically efficient. The costs and energy used in collection and transport compared to the costs and energy saved in the production process have been debated.

Renewable. In sustainable development, this relates to a commodity or resource, such as solar energy or firewood, that is inexhaustible or replaceable by new growth. The opposite is finite resources, such as fossil fuels, which are definitely exhaustible. The meaning is extended by including emissions. By dint of being replaceable within a relatively short time frame, renewable resources are more likely to be carbon-neutral as the emissions from their use can be negated by CO_2 capture during growth. As fossil resources take millions of years to develop, the emissions generated are considered "permanent" as the time frames nullify the original carbon capture (millions of years ago) in relation to the human lifespan.

Renewable Energy Directive (RED). Officially titled as 2009/28/EC, this is an EU directive that mandates levels of renewable energy use within the European Union. The directive was published on 23 April 2009 and amends and repeals the 2001 Directive on Electricity Production from Renewable Energy Sources. It requires the European Union to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020. A new Renewable Energy Directive for the period after 2020 is in preparation.

Renewable energy tax credit. This is any tax credit offered by a local or federal taxation authority as an incentive for the installation and operation of renewable energy systems such as solar or wind power. Renewable power generation creates power in the form of electricity, and environmental benefits to society from "green" power production – such as minimising pollution and slowing the rate at which finite fuel resources are used. The electricity is sold into the local grid, and the societal benefits are sold in the form of renewable energy credits (RECs), sold separately as a commodity into the marketplace. For each REC purchased, customers can claim the equivalent MWh of energy reduction as an offset to their conventional energy use.

Renewable feedstock. This can be defined as any renewable, biological material that can be used directly as a fuel, or converted to another form of fuel, energy or bio-based material product. Biomass feedstocks are the plant and algal materials used to derive fuels like ethanol, butanol, biodiesel and other hydrocarbon fuels. Organic wastes are assuming greater importance politically as renewable feedstocks.

Renewable Fuels Standard (RFS). The RFS is a US federal programme that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels. The RFS originated with the Energy Policy Act of 2005 and was expanded and extended by the Energy Independence and Security Act of 2007 (EISA).

Salination. Soil salinity is the salt content in the soil; the process of increasing the salt content is known as salination or salinisation. Salts occur naturally within soils and water. Salination can be caused by natural processes such as mineral weathering or by the gradual withdrawal of an ocean. Salinity from irrigation can occur over time wherever irrigation occurs, since almost all water contains some dissolved salts. Soil salinity has detrimental effects on plant growth and yield.

Secondary refining. Further conversion and processing steps create a larger number of products from the intermediates. Thereby, in a first conversion step, the intermediate materials are fully or partially processed into precursors, as well as into more intermediates;

in further value creation at the site of the biorefinery, these are then fully or partially refined into products. The products from biorefineries can be both finished or semi-finished.

Slash. The component within the forest residues generated from sawlog processing typically consisting of chunks, foliage, branches and other broken material not appropriate to be comminuted by a chipper.

Small to medium-sized enterprise (SME). In the European Union, an SME can be defined as a firm with revenues of EUR 10-50 million or a balance-sheet total of EUR 10-43 million. In general, an SME has up to about 250 employees. SMEs are very common in biotechnology, especially in research-intensive firms. Many firms are involved in industrial biotechnology and attempt to make sustainable alternatives to fossil-derived goods.

Soil destruction. Soil destruction can include soil erosion. Soil can also be destroyed by salination, over-fertilisation and industrial pollution. If, for example, a soil becomes so contaminated with heavy metals from industry that it cannot be used in agriculture, it would be considered "destroyed", although the soil itself remains.

Soil erosion. Soil erosion is defined as the wearing away of topsoil. Topsoil is the top layer of soil and is the most fertile because it contains the most organic, nutrient-rich materials. Therefore, this is the layer that farmers want to protect for growing their crops and animals. Soil erosion can have several causes. A prime concern in sustainability is erosion caused by deforestation.

Solvent. This is a liquid, typically other than water, used for dissolving other substances. Often solvents are non-polar liquids that are toxic to humans and pose threats to the environment if released accidentally. Another major function of solvents is to clean surfaces, and biodegradable solvents have been developed as potential replacements for more harmful solvents in such applications.

Specialty chemicals. Single molecules or mixtures valued for their particular abilities – for example, killing bacteria or fire retardation.

Starch. A molecule composed of long chains of glucose molecules linked together (repeating unit $C_{12}H_{16}O_5$). This polysaccharide is widely distributed in the vegetable kingdom and is stored in all grains and tubers.

Starch biorefinery. The component separation in primary refining results in starch, which thus constitutes the platform of the starch biorefinery. Typical feedstocks are cereals or potatoes.

Steam explosion. This is a pre-treatment process in which biomass is treated with hot steam under pressure followed by an explosive decompression of the biomass that results in a rupture of the biomass fibres rigid structure, literally "exploding" the biomass to pulp. It makes the biomass polymers more accessible for subsequent processes, such as fermentation, hydrolysis or densification.

Stover. The dried stalks and leaves of a crop that remain after the grain has been harvested.

Sugar biorefinery. Sucrose, commercially available sugar, results from separation processes, and the sugar is then converted, usually through fermentation, to products such as ethanol. Typical feedstocks are sugar cane and sugar beet.

Supply chain. A network of individuals or organisations that procures materials; transforms these materials into intermediate and finished products; and distributes finished products to customers.

Sustainable development goals (SDGs). These are an inter-governmental set of 17 aspiration goals with 169 targets. The goals are contained in paragraph 54 of the United Nations Resolution A/RES/70/1, of 25 September 2015. They are officially known as Transforming our World: the 2030 Agenda for Sustainable Development. They include ending poverty and hunger, improving health and education, making cities more sustainable, combating climate change, and protecting oceans and forests.

Sustainability. This term is in common use, but is hard to define. Human and ecological sustainability have become intermingled with the emergence of climate change as a major societal challenge. Defining sustainability as a part of the concept of sustainable development, the Brundtland Commission of the United Nations in 1987 stated that: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It reflects the realisation that economic growth must be achieved with minimal environmental damage if the effects of climate change are to be controlled.

Sustainability indicators. Ecological and environmental indicators have been intermingled in assessing sustainability. One subset of environmental indicators is ecological indicators that include physical, biological and chemical measures such as atmospheric temperature or the concentration of ozone in the stratosphere. These are also referred to as "state" indicators as their focus is on the state of the environment or conditions in the environment. A second subset is indicators that measure human activities or anthropogenic pressures, such as greenhouse gas emissions. These are also referred to as "pressure" indicators, i.e. they measure the pressures that humans place on the environment. Finally, there are indicators, such as the number of people served by sewage treatment, which track societal responses to environmental issues.

Synthesis gas (syngas). The product of gasification i.e. CO, H_2 and CO_2, a mixture of which is in itself a fuel.

Synthesis gas biorefining. Here there is no separate component separation during primary refining; instead, all organic constituents (e.g. solid domestic waste) and biomass components are broken down in such a way to produce the raw product synthesis gas. This makes materials amenable for biorefining that would otherwise be unsuited. Products range from fuels, such as Fischer-Tropsch diesel and methanol, to higher alcohols and chemicals, and chemicals.

Synthetic biology. The application of science, technology and engineering to facilitate and accelerate the design, manufacture and/or modification of genetic materials in living organisms. It aims to bring an engineering approach to biotechnology by design and engineering of biologically-based parts, novel devices and systems, as well as redesigning existing, natural biological systems. It has clear and current applications to bio-production of chemicals, plastics, textiles and other materials.

Thermochemical conversion. The use of heat to chemically change substances to produce energy products.

Torrefaction. Torrefaction of biomass is a mild form of pyrolysis at temperatures typically between 200°C and 320°C. It changes biomass properties to provide a much better fuel quality for combustion and gasification applications. It leads to a dry product that is stable on storage as rotting can no longer occur. It can also result in much higher energy density, useful to improve transportation efficiency.

Transcriptomics. The transcriptome is the complete set of transcripts in a cell, and their quantity, for a specific developmental stage or physiological condition. Transcriptomics therefore is the study of genes being expressed at any given time under given conditions.

Transesterification. Biodiesel can be produced from straight vegetable oil (SVO), animal oil/fats, tallow and waste oils. SVO creates fairly severe engine problems such as poor atomisation. Transesterification is the reaction of a triglyceride (fat/oil) with an alcohol to form esters (the biodiesel) and glycerol. The glycerol is relatively simple to separate, and the biodiesel has much enhanced properties as a diesel fuel.

Value added. The additional value, in customer terms, created at a particular stage of production.

Value chain. The value chain identifies the various value-adding activities of an organisation or network. It is often used as a tool for strategic planning because of its emphasis on maximising value while minimising costs.

Vegetable oil biorefinery. A biorefinery in which the feedstock is oil from various seeds and fruits, whereby oil is present together with other lipids.

Waste. This means any substance or object which the holder discards or intends to, or is required to, discard. This narrow definition avoids the implication that the material or object serves no further use. In the context of sustainability, waste minimisation is an important concept. Billions of tonnes of organic waste materials are produced worldwide every year, and a great deal of these waste materials could be used as a source of biomass for the production of bio-based materials.

Waste hierarchy. Waste disposal legislation has introduced a hierarchy of options for managing wastes. It gives top priority to preventing waste in the first place. When waste is created, it gives priority to preparing it for reuse, then recycling, then other recovery such as energy recovery, and last of all disposal, e.g. landfill.

Waste-to-energy. The practice of processing waste products to generate steam, heat or electricity.

Wastewater and wastewater treatment. Wastewater is any water that has been adversely affected in quality by human influence. Wastewater can originate from a combination of domestic, industrial, commercial or agricultural activities, surface run-off or storm water, and from sewer inflow or infiltration. Wastewater treatment is the process whereby wastewater is treated to render it innocuous and/or reusable. Biological wastewater treatment plants, known more widely as sewage treatment plants, are more sustainable than non-biological processes and are deployed worldwide. Wastewater treatment and reuse is considered essential to future water security.

Water security. The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems.

Zero waste. The goal of developing products and services, managing their use and deployment, and creating recycling systems and markets to eliminate the volume and toxicity of waste and materials, and conserve and recover all resources. Implementing zero waste eliminates all discharges to land, water or air that may be a threat to planetary, human, animal or plant health.

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