Written evidence from Biomass Biorefinery Network, Supergen Bioenergy Hub (ENB0041)

The Supergen Bioenergy Hub is a UKRI funded research consortium focusing on sustainable biomass and bioenergy systems. The Biomass Biorefinery Network (BBNet) is a network of industrial and academic practitioners working on the conversion of non-food biomass into sustainable fuels, chemicals and materials.

Industrial biotechnology and engineering biology

Industrial Biotechnology is the use of biological systems, including enzymes, micro-organisms, cells, or whole organisms, to make products such as chemicals, energy, or materials. Industrial biotechnology can use biological systems that have been modified using synthetic biology or make use of naturally occurring systems (e.g., fermentation using an un-modified bacteria or bio-catalysis using a naturally occurring enzyme). The UK has a strong history of research activity in industrial biotechnology, which has the potential to deliver economic and social benefits and see the UK become a leader in this space [1].

Under the government definition of engineering biology outlined in the national vision for engineering biology, it appears that industrial biotechnology applications that make use of un-modified biological systems (including some of the examples given below) may fall under the umbrella of engineering biology, whereas the UKRI definition clearly excludes such systems [2, 3]. This discrepancy is reflected in the different understanding of engineering biology we have encountered amongst our stakeholder community, with some seeing the government's approach to engineering biology as being a broad term for many bioeconomy applications and other seeing it as a narrow term which is essentially an evolution of synthetic biology. Our concern is that uncertainty around the definition will result in some of those who have historically been involved in the UK's industrial biotechnology activity will get left behind in the drive forward on engineering biology. To effectively build on previous UK strength and activities in this space we believe a clear and unified definition for engineering biology is needed, alongside a plan for building upon wider industrial biotechnology and bioeconomy activities if they are excluded from the government's activities around engineering biology.

Key applications for engineering biology

Here we will highlight several exciting and important applications of engineering biology that are of particular relevance to the work of the Supergen Bioenergy Hub and the Biomass Biorefinery Network.

Many of these applications relate to the conversion of a biomass (or CO_2) feedstock into a product such as a chemical or fuel. Often these feedstocks can also be converted into valuable products using non-biological processes (e.g., chemical, catalytic, thermochemical, electrolytic). Using a biological process can have a number of benefits over alternative conversion technologies: high specificity in terms of the feedstocks used and the product made, ability to use a number of otherwise challenging feedstocks, simplified (or shortened) synthesis of complex molecules, ability to produce molecules not possible via other routes, and mild conditions (fewer harsh chemicals, lower temperatures, lower energy demand) [4-6]. Biological systems can also allow some of the complex chemical structures found in biomass feedstocks to be retained in chemical products, whereas other processes tend to completely break down the feedstock meaning complexity must be rebuilt through synthetic steps. However, there are also limitations to biological processes. For example, high water demand and complex downstream processing requirements can be problematic, and there can be limitations as to the scale of production that can be achieved [4, 6-8]. In essence, it is important to be clear that industrial biotechnology/ engineering biology will not be the right approach to every product or challenge, but it has great promise in some cases.

Bearing the above discussion around the definition of engineering biology, it is also important to highlight the additional benefits that can be gained through synthetic biology processes and engineered organisms. Modification of organisms for use in industrial biotechnology can be used to expand the range of feedstocks that can be used, unlock new products, and improve performance under industrial conditions (e.g., increased rate or improved stability) [9, 10].

Although biological processes are already being used to make a variety of products at industrial scale, many of the products/processes described below have been demonstrated at lab scale only. In many cases there are still research challenges to be addressed to fully unlock their potential, as well as the various technical and non-technical challenges associated with scale up and deployment.

Chemicals and materials

Currently, many of the chemicals and materials we use are dervied from carbon in fossil feedstocks and this eventually results in fossil carbon being released to the atmosphere [11-15]. To transition away from the use of fossil feedstocks for chemicals, they must be replaced with renewable carbon sources such as biomass [11, 14-16]. Bio-based chemicals and materials potentially have reduced greenhouse gas (GHG) emissions compared to fossil-based products [17-19]. As well as being able to use biomass to make drop-in replacements for exisiting chemicals, there opporutntities for new products with beneficial properties.

Examples of chemicals and materials produced using industrial biotechnology include polymers and plastics (such as the biodegradable polymers PLA (polylactic acid) and PHA (polyhydroxyalkanoates)), platform chemicals (including drop-in platform chemicals like ethylene, and novel bio-based platforms), surfactants (speciality chemicals properties that are used in a vast array of products as cleaning agents or stabilisers), and higher value bio-based products (such as fine chemicals, and novel pharmaceuticals, dyes, and agrichemicals) [17, 19-35]. The UK has a lot of activity in this space, with some being scaled up. For example, an exciting UK company working on bio-surfactant production is Holiferm, a spin out from the University of Manchester with a commercial demonstration plant in Merseyside and ongoing partnerships with a number of large chemical companies [32, 33, 36, 37]. A number of platform chemicals have also been highlighted as particular opporutntities for the UK [38, 39].

CO_2 utilisation

Gas fermentation can be used to make a variety of useful chemical products from CO_2 (with hydrogen) and other single carbon (C1) gases such as (bio)methane. Gas fermentation is the microbial conversion of these gases into products [40, 41]. Gas fermentation is a less mature technology than sugar fermentation, but some examples are starting to reach commercial scale, and engineering biology is expanding the variety of products that might be accessible via this route [40, 42]. The Nottingham Synthetic Biology Research Centre has significant expertise in this area and hosts the Carbon Recycling Network [43]. As is the case with biomass processing, there are also non-biological routes being developed for conversion of CO_2 but the energy requirement for CO_2 conversion is always a significant challenege.

Biological processes such as fermentation and anaerobic digestion also release biogenic CO_2 as a by-product, sometimes in significant quantities. Biological approaches to utilising this CO_2 would increase the conversion efficiency of the process (i.e., getting more product from the same amount of feedstock), but there is also the potential to link such processes to carbon capture and storage, reducing the lifecycle GHG emissions and potentially enabling negative emissions.

Fuels

Decarbonisation of the energy systems is essential for meeting climate targets. Although in many cases this will be done through electrification, some applications will still require deployable fuels, particularly in the short/ medium term. Biological processes can be used in the production of biofuels, for example for transport (e.g., ethanol, SAF) and heating.

Waste biorefining and circular economy

Industrial biotechnology can be used to convert of wastes (e.g., food waste and waste from industrial food production, municipal solid waste, sewage) and residues (e.g., agricultural residues such straw or slurry) (or in some cases sugars derived from waste feedstocks) into the kinds of valuable products described above. It can also be used to breakdown materials to enable recycling, or to extract and purify valuable compounds found in waste materials [44, 45]. Doing so not only supports the transition to a circular economy but can reduce the impacts of pollution and avoid GHG emissions from breakdown of biodegradable waste such as food in landfills or the envrionment. An example of waste biorefining activity in the UK is found in Celtic Renewables, whose plant will produce acetone, butanol and ethanol from local distillery residues [24].

There are some types of waste where the unique properties of biological systems can be used to overcome challenges faced by other recycling technologies. For example, research has shown that bio-based processes could improve recycling of some textile materials, breaking down the textiles into their component parts and in some cases even re-generating virgin quality fibres from textile waste [9]. Huge quantities of textile waste are produced each year and for many common textile materials there are challenges with recycling, for example due to blended fibres or the presence of contaminants (e.g., dyes) [9, 46]. One benefit is that the specificity of biological systems mean they can overcome the challenges associated with mixed fibre recycling. Similarly, there are challenges associated with effective recycling of some plastic and electronic waste where biological systems show some promise [10, 47].

Barriers and limitations to good and effective use of engineering biology

The priority areas of R&D, infrastructure for scale up, talent and skills, regulations and standards, finance, and responsible innovation laid out in the National Vision for Engineering Biology reflect many of the key barriers that have come up in discussions with our communities, and in some cases also reflect issues relating to the wider bioeconomy. Other barriers or challenges highlighted by our community include feedstock availability, markets and cost competitiveness, and uncertainty around sustainability impacts.

R&D

Continued, excellent research will be essential to unlocking the potential of the engineering biology applications discussed above. Key enabling technologies such as CRISPR Cas and DNA sequencing will continue to be important. Critically, successful, and sustainable deployment of engineering biology will require interdisciplinary research, often requiring input not just from biological sciences, but other disciplines such as chemical engineering, sustainability assessment, chemistry, economics, social sciences, and computation fields such as AI and bioinformatics. It is also important to recognise that the innovation, commercialization scale-up that will be required has been successfully demonstrated in other disciplines, so collaboration and interdisciplinary embodiment is key.

Feedstock availability

Availability of sufficient feedstock of suitable nature and quality is important for those scaling and deploying engineering biology applications, as is security of the feedstock supply chain. Many engineering biology applications will require sugars or other inputs derived from biomass feedstocks. Biomass feedstocks include dedicated crops (e.g., wheat, maize, or sugar beet, or perennials such as miscanthus and willow), algae, agricultural residues (e.g., straw and manure), forestry biomass, and other biogenic wastes and residues (e.g., food waste). However, sugar and other biomass feedstocks are not unique to engineering biology applications: they have applications across the bioeconomy and in some cases, there is also competition with food production. It is therefore improtant that discussions around availability of feedstocks for engineering biology do not happen in isolation but occur as part of the wider discussion around biomass feedstock availability.

Research has shown that the UK can access significant amounts of biomass feedstock from both domestic and international sources, but in the future, there will likely be increased competition for this resoruce from the different applications [48, 49]. Which application represents the "best use" of biomass depends on what the main objective is: economic growth, decarbonisation, etc. The Biomass Strategy that was published by the UK government last year indicates that biomass use will be prioritised to support the UK's net zero targets, particularly through applications that deliver negative emissions and to support decarbonisation of sectors that cannot be addressed in other ways (e.g., aviation fuel) [50]. This could mean there are challenges around feedstock availability and supply chains for some applications of engineering biology that do not contribute to these decarbonisation priorities.

We feel that one sector not adequately reflected in the priorities laid out in the Biomass Strategy was the use of biomass in the chemicals sector, because biomass represents one of the only routes for this sector to transition away from the use of fossil feedstocks [11-16].

Questions around feedstock availability also led to the question of whether the UK would be better placed to focus on low volume high value products from engineering biology, instead of bulk products such as fuels or high-volume platform chemicals and plastics. Again, this depends on what the main objective is. Though bulk products would demand a greater share of the UK's biomass feedstock they would also enable greater GHG reductions overall because of the volumes being considered. It is critical that such potential is judged on their ability to support the UK economy (one pillar of sustainability) but also their environmental and social benefits.

Steps that could support secure supply of domestic biomass feedstocks in the UK for future applications of engineering biology include measures to encourage domestic planting and changes to regulation to better enable the valorisation of waste. The UK bioeconomy could also benefit from technologies that allow exploitation of a wider variety of feedstocks, such as technologies for scalable and cost-effective release of sugar from lignocellulosic biomass. Lignocellulosic biomass, which includes wood (e.g., forestry residues), perennial crops (e.g., miscanthus or willow), and agricultural residues such as straw), is harder to process than feedstocks like sugar crops. It requires pre-treatment processes to release the sugars and this can increase costs and energy requirements [8, 19, 51-54]. Several UK based companies are scaling up new technologies in this space [51, 53, 55, 56].

Sustainability

Bioeconomy technologies come with potential sustainability risks and benefits, relating to climate, wider environmental impacts (e.g., relating to land and ecosystems and water), people, and the economy [57]. The sustainability risks of technologies, products, and feedstocks should be considered. Wider awareness and focus on sustainability are needed at all stages of the innovation process, as well as during technology deployment and policy development.

Different biomass feedstocks that might be used for engineering biology come with different sustainability risks and benefits. Previous work from the Supergen Bioenergy Hub has indicated the need for rigorous approaches to sustainability governance for biomass feedstocks, with criteria that are harmonised across sectors and that go beyond GHG emissions to include wider environmental impacts [58, 59].

Engineering biology can be used to enable more sustainable manufacturing and products with lower GHG emissions or other environmental benefits, but it is improtant to be clear that the use of industrial biotechnology, engineering biology, or bio-based feedstocks does not guarantee a process or product will be more sustainable than that which it would replace [4, 6, 17-19, 22, 60, 61]. Evidence on the sustainability performance of new technologies and products will be improtant to ensure that engineering biology technologies that are being developed due to potential sustainability benefits, deliver those benefits.

Markets and costs

We have particularly considered the issue of markets and cost competitiveness of bio-based chemicals, including those produced through industrial biotechnology and engineering biology. Many of these products will be more expensive than those which they might displace, and this will be a barrier to their development and uptake even if they can deliver sustainability benefits or improved performance. There are ways that research can seek to create more cost competitive products but competition fossil-based products is likely to be a continued challenege, particularly as there currently no regulatory or policy mechanism that incentivises the production of chemicals with lower lifecycle emissions or chemcials produced from renewable feedstocks instead of fossil fuels.

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References:

[1] Institute for Manufacturing University of Cambridge, Life sciences beyond human health: modern industrial biotechnology in the UK, 2023. https://www.ciip.group.cam.ac.uk/media/uploads/files/Industrial_Biotech_-_Report_vPUBLICATION_240323.pdf.
[2] National Vision for Engineering Biology
[3] UKRI Engineering Biology Missions Hubs and Mission Awards. https://www.ukri.org/opportunity/engineering-biology-missions-hubs-and-mission-awards/.
[4] J.M. Woodley, M. Breuer, D. Mink, A future perspective on the role of industrial biotechnology for chemicals production, Chemical Engineering Research and Design 91(10) (2013) 2029-2036.
[5] United Nations Environment Programme, Global Chemicals Outlook II, 2019. https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions.
[6] T.A. Ewing, N. Nouse, M. van Lint, J. van Haveren, J. Hugenholtz, D.S. van Es, Fermentation for the production of biobased chemicals in a circular economy: a perspective for the period 2022–2050, Green Chemistry 24(17) (2022) 6373-6405.
[7] J. Philp, The bioeconomy, the challenge of the century for policy makers, New Biotechnology 40 (2018) 11-19.
[8] J. Louw, E.S. Dogbe, B. Yang, J.F. Görgens, Prioritisation of biomass-derived products for biorefineries based on economic feasibility: A review on the comparability of techno-economic assessment results, Renewable and Sustainable Energy Reviews 188 (2023).
[9] M. Ribul, A. Lanot, C.T. Pisapia, P. Purnell, S.J.M. Mason, S. Baurley, Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles Journal of Cleaner Production 326 (2021).
[10] A. Singh, N.A. Rorrer, S.R. Nicholson, E. Erickson, J.S. DesVeaux, A.F.T. Avelino, P. Lamers, A. Bhatt, Y. Zhang, G. Avery, L. Tao, A.R. Pickford, A.C. Carpenter, J.E. McGeehan, G.T. Beckham, Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate), Joule 5(9) (2021) 2479-2503.
[11] Nova Institue, Turning off the Tap for Fossil Carbon, 2021. https://renewable-carbon.eu/publications/product/turning-off-the-tap-for-fossil-carbon-future-prospects-for-a-global-chemical-and-derived-material-sector-based-on-renewable-carbon/.
[12] Renewable Carbon Inititative, Carbon Flows Report, 2023. https://renewable-carbon.eu/publications/product/the-renewable-carbon-initiatives-carbon-flows-report-pdf/.
[13] International Energy Agency, The Future of Petrochemicals 2018. https://www.iea.org/reports/the-future-of-petrochemicals.
[14] Science Based Targets, Barriers, Challenges, and Opportunities for Chemical Companies to Set Science-Based Targets, 2020.

https://sciencebasedtargets.org/resources/files/SBTi-Chemicals-Scoping-Document-12.2020.pdf.
[15] P. Stegmann, V. Daioglou, M. Londo, D.P. van Vuuren, M. Junginger, Plastic futures and their CO(2) emissions, Nature 612(7939) (2022) 272-276.
[16] A. González-Garay, N. Mac Dowell, N. Shah, A carbon neutral chemical industry powered by the sun, Discover Chemical Engineering 1(1) (2021).
[17] B. Winter, R. Meys, A. Sternberg, A. Bardow, Sugar-to-What? An Environmental Merit Order Curve for Biobased Chemicals and Plastics, ACS Sustain Chem Eng 10(48) (2022) 15648-15659.
[18] E.A.R. Zuiderveen, K.J.J. Kuipers, C. Caldeira, S.V. Hanssen, M.K. van der Hulst, M.M.J. de Jonge, A. Vlysidis, R. van Zelm, S. Sala, M.A.J. Huijbregts, The potential of emerging bio-based products to reduce environmental impacts, Nat Commun 14(1) (2023) 8521.
[19] IEA Bioenergy Task 42, Bio-Based Chemicals: A 2020 Update https://task42.ieabioenergy.com/wp-content/uploads/sites/10/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf.
[20] High Value Biorenewables Network, Using biological systems to develop high value products, 2024. https://www.highvaluebiorenewables.net/policy/.
[21] Royal Society of Chemistry, Polymers in liquid formulations Technical report: A landscape view of the global PLFs market, 2021. https://www.rsc.org/globalassets/22-new-perspectives/sustainability/liquid-polymers/rsc-polymer-liquid-formulations-technical-report.pdf.
[22] J.-G. Rosenboom, R. Langer, G. Traverso, Bioplastics for a circular econonmy Nature Reviews Materials 7 (2022) 117–137
[23] A.Z. Naser, I. Deiab, B.M. Darras, Poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review RSC Adv 11 (2021) 17151-17196.
[24] Celtic Renewables https://www.celtic-renewables.com/.
[25] F.G. Calvo-Flores, M.J. Monteagudo-Arrebola, J.A. Dobado, J. Isac-Garcia, Green and Bio-Based Solvents, Top Curr Chem (Cham) 376(3) (2018) 18.
[26] J. Rios, J. Lebeau, T. Yang, S. Li, M. Lynch, A Critical Review on the Progress and Challenges to a More Sustainable, Cost Competitive Synthesis of Adipic Acid, Green Chemistry (2021).
[27] Braskem, I'm green polyethylene http://plasticoverde.braskem.com.br/site.aspx/Im-greenTM-Polyethylene.
[28] A. Mohsenzadeh, A. Zamani, M.J. Taherzadeh, Bioethylene Production from Ethanol: A Review and Techno-economical Evaluation, ChemBioEng Reviews 4(2) (2017) 75-91.
[29] D.S. Pardhi, R.R. Panchal, V.H. Raval, R.G. Joshi, P. Poczai, W.H. Almalki, K.N. Rajput, Microbial surfactants: A journey from fundamentals to recent advances, Front Microbiol 13 (2022) 982603.
[30] E. Guzmán, F. Ortega, R.G. Rubio, Exploring the World of Rhamnolipids: A critical review of their production, interfacial properties, and potential application, Current Opinion in Colloid & Interface Science (2023).
[31] https://www.unilever.com/news/news-search/2022/building-a-clean-green-foamproduction-machine/ and https://household-care.evonik.com/en/products/biosurfactants.
[32] Holiferm and Sasol Chemicals expand collaboration to develop and market sustainable surfactants. https://www.sasol.com/holiferm-and-sasol-chemicals-expand-collaboration-develop-and-market-sustainable-surfactants.
[33] BASF strengthens its position in bio-surfactants for Personal Care, Home Care and Industrial Formulators with two distinct partnerships, 2021.

https://www.basf.com/hk/en/media/news-releases/global/2021/03/p-21-148.html.
[34] S. Stubbs, S. Yousaf, I. Khan, A review on the synthesis of bio-based surfactants using green chemistry principles, Daru 30(2) (2022) 407-426.
[35] A. Bhadani, A. Kafle, T. Ogura, M. Akamatsu, K. Sakai, H. Sakai, M. Abe, Current perspective of sustainable surfactants based on renewable building blocks, Current Opinion in Colloid & Interface Science 45 (2020) 124-135.
[36] Holiferm. https://holiferm.com/.
[37] https://fibenol.com/news/holiferm-and-fibenol-join-forces-to-develop-sustainable-biosurfactants-from-wood-residues.
[38] LBNet, UKBioChem10 - The ten green chemicals which can create growth, jobs and trade for the UK, 2019. http://ukbiochem10.co.uk/wp/wp-content/uploads/2019/01/UKBioChem10_Report.pdf.
[39] E4tech (UK) Ltd for LBNet, UK Top Bio-based Chemicals Opportunities, 2017. https://www.bbnet-nibb.co.uk/wp-content/uploads/2019/08/LBNet-UKBioChem10_UK-Top-Bio-based-Chemicals-Opportunities_Dec2017.pdf.
[40] F.E. Liew, R. Nogle, T. Abdalla, B.J. Rasor, C. Canter, R.O. Jensen, L. Wang, J. Strutz, P. Chirania, S. De Tissera, A.P. Mueller, Z. Ruan, A. Gao, L. Tran, N.L. Engle, J.C. Bromley, J. Daniell, R. Conrado, T.J. Tschaplinski, R.J. Giannone, R.L. Hettich, A.S. Karim, S.D. Simpson, S.D. Brown, C. Leang, M.C. Jewett, M. Kopke, Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale, Nat Biotechnol 40(3) (2022) 335-344.
[41] M. Kopke, S.D. Simpson, Pollution to products: recycling of 'above ground' carbon by gas fermentation, Curr Opin Biotechnol 65 (2020) 180-189.
[42] E. Marcellin, L.T. Angenent, L.K. Nielsen, B. Molitor, Recycling carbon for sustainable protein production using gas fermentation, Curr Opin Biotechnol 76 (2022) 102723.
[43] https://www.sbrc-nottingham.ac.uk/about/about.aspx#:~:text=Our%20centre%20uses%20engineering%20biology%20approaches%20to%20understand,greenhouse%20gases%3A%20carbon%20monoxide%2C%20carbon%20dioxide%20and%20methane. and https://carbonrecycling.net/.
[44] High Value Biorenewables Network, UK Grown Review 2022. https://www.highvaluebiorenewables.net/news/uk-grown-review/.
[45] A. Dornau, J.F. Robson, G.H. Thomas, S.J. McQueen-Mason, Robust microorganisms for biofuel and chemical production from municipal solid waste, Microb Cell Fact 19(1) (2020) 68.
[46] Ellen MacArthur Foundation, A New Textiles Economy: Redesigning fashion’s future.
[47] I. Tezyapar Kara, K. Kremser, S.T. Wagland, F. Coulon, Bioleaching metal-bearing wastes and by-products for resource recovery: a review, Environmental Chemistry Letters 21(6) (2023) 3329-3350.
[48] A. Welfle, R.A. Holland, I. Donnison, P. Thornley, Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report. Supergen Bioenergy Hub Report No. 02/2020. https://www.supergen-bioenergy.net/wp-content/uploads/2020/10/Supergen-Bioenergy-HubUK-Biomass-Availability-Modelling-Scoping-Report-Published-Final.pdf.
[49] A. Welfle, P. Gilbert, P. Thornley, Securing a bioenergy future without imports, Energy Policy 68 (2014) 1-14.
[50] Department for Energy Security and Net Zero, Biomass Strategy 2023. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1178897/biomass-strategy-2023.pdf.

[51] Biomass Biorefinery Network, Pre-treatments to enhance the enzymatic saccharification of lignocellulose: technological and economic aspects, 2021. https://www.bbnet-nibb.co.uk/wp-content/uploads/2021/02/BBNet-Pretreatment-Tech-Review-Feb2021-.pdf.
[52] E4tech Ltd for LBNet, An assessment of the potential for the establishment of lignocellulosic biorefineries in the UK, (2016).
[53] A. Brandt-Talbot, F.J.V. Gschwend, P.S. Fennell, T.M. Lammens, B. Tan, J. Weale, J.P. Hallett, An economically viable ionic liquid for the fractionation of lignocellulosic biomass, Green Chemistry 19(13) (2017) 3078-3102.
[54] T. Pielhop, J. Amgarten, P.R. von Rohr, M.H. Studer, Steam explosion pretreatment of softwood: the effect of the explosive decompression on enzymatic digestibility, Biotechnol Biofuels 9 (2016) 152.
[55] E4tech, Ramp up of lignocellulosic ethanol in Europe to 2030, 2017. https://uploads-ssl.webflow.com/643691764f0ee331841022ac/643691764f0ee3cf0b102898_2017_E4tech_Ramp-up-of-lignocellulosic-ethanol-in-europe-to-2030.pdf.
[56] A.R. Mankar, A. Pandey, A. Modak, K.K. Pant, Pretreatment of lignocellulosic biomass: A review on recent advances, Bioresour Technol 334 (2021) 125235.
[57] A. Welfle, M. Röder, Mapping the sustainability of bioenergy to maximise benefits, mitigate risks and drive progress toward the Sustainable Development Goals, Renewable Energy 191 (2022) 493-509.
[58] A.J. Welfle, A. Almena, M.N. Arshad, S.W. Banks, I. Butnar, K.J. Chong, S.G. Cooper, H. Daly, S. Garcia Freites, F. Güleç, C. Hardacre, R. Holland, L. Lan, C.S. Lee, P. Robertson, R. Rowe, A. Shepherd, N. Skillen, S. Tedesco, P. Thornley, P. Verdía Barbará, I. Watson, O.S.A. Williams, M. Röder, Sustainability of Bioenergy – Mapping the Risks & Benefits to Inform Future Bioenergy Systems, Biomass and Bioenergy 177 (2023).
[59] C. Cucuzzella, A. Welfle, M. Röder, Harmonising greenhouse gas and sustainability criteria for low-carbon transport fuels, bioenergy and other bio-based sectors Supergen Bioenergy Hub and Low Carbon Vehicle Partnership Collaboration Project Report. Supergen Bioenergy Hub Report No. 04/2020, 2020. https://www.supergen-bioenergy.net/wpcontent/uploads/2020/11/Harmonising-sustainability-standards-report.pdf.
[60] S. Walker, R. Rothman, Life cycle assessment of bio-based and fossil-based plastic: A review, Journal of Cleaner Production 261 (2020).
[61] A. Santos, A. Barbosa-Póvoa, A. Carvalho, Life cycle assessment in chemical industry – a review, Current Opinion in Chemical Engineering 26 (2019) 139-147.