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Harnessing Synthetic Biology to Meet the 2030 UN Sustainable Development Goals

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Advances in genetic engineering have placed synthetic biology at a prime position to develop new products, materials, and services that could contribute to the 2030 UN Sustainable Development goals. These include novel materials for water purification, new bio-based products to replace toxic industrial chemicals, and engineered organisms for bioremediation. Supporting the development of synthetic biology initiatives in developing countries is needed to ensure these benefits are open to all.

In 2015, the United Nations put forth 17 Sustainable Development goals which emphasize the need to promote access to health care and education, to maintain and conserve earth's natural resources, and to develop new technologies to transition to a more sustainable society by 2030.[1] The organisms, materials, and other services produced using synthetic biology could advance these goals (**Fig. 1**).[2,3] The field of synthetic biology is highly interdisciplinary and rapidly growing—embracing techniques and ideas from biology, engineering, chemistry and materials sciences. Synthetic biology brings two key contributions to the sustainability table: (1) understanding how organisms respond to and adapt to their environment, from single cells to complex communities; and (2) a diverse tool-set for abstracting, manipulating and applying this knowledge to solve pressing global issues. Current industrial processes, consumption habits, and intensive agriculture threaten the stability of human societies and ecosystems worldwide.[4] Although synthetic biology cannot solve all the world's problems, it can provide innovations which can lead to a more sustainable future.

Here, I outline the key areas where synthetic biology could contribute to the UN Sustainable Development Goals while also pointing out the changes needed within the field to achieve this vision. These changes include the need to support synthetic biology in developing countries and the need for increased policy to mitigate the social and environmental risks posed by biologically engineered organisms and materials.

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Figure 1 A bio-based future. Examples of how synthetic biology could revolutionize society include the industrial production of plant compounds like palm oil (left) to reduce human pressure on land; new air filters based on the ability of plane trees (center) to remove pollutants from the environment; and the creation of sustainable pigments based on structural color found in natural systems like *Pollia condensata* (right) to replace toxic chemicals used in dye and clothing industries. Image credits: palm oil fruits (Pixaby); London Plane tree (Pixaby); *Pollia condensate* fruit (Silvia Vignolini et al. via PNAS).

Extending synthetic biology's reach

Synthetic biology could contribute to eight Sustainable Development Goals (Table 1). These contributions range from the development of new products through the exploitation of biological materials (e.g. proteins, carbohydrates, surfactants) to new innovations that support the restoration of ecosystem services. Four areas where synthetic biology could contribute most are:

- reducing the use of harmful industrial chemicals by providing biologically-based alternatives
- cleaning up environmental pollutants
- increasing crop productivity and soil health
- replacing synthetic, non-renewable materials with those derived from organic sources.

These contributions coincide with Goals 6, 9, 14 and 15. While some of the potential applications listed in **Table 1** may seem far-fetched, they are grounded in recent scientific advances. These include the production of bioplastics from wheat proteins, potato starch, and bacterial storage compounds (polyhydroxyalkanoates, PHAs)[5-7]; the development of sensors based on odorant-binding proteins, neural receptors, and RNAs from a wide range of organisms[8,9]; and the creation of new pigments by re-engineering the proteins responsible for the optical properties of silica and cellulose.[10-12] In order to ensure fundamental research is translated into usable products and services, several changes within synthetic biology practice are needed. These changes include overcoming the technical issues of scaling up; increasing dialogue between scientists, NGOs, and industry during the innovation process to ensure usefulness of the final product/service); and reducing the risk associated with high-risk high-reward research to attract investment.

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The innovations described above could be used to stir bioeconomies in developing countries (Goals 9 and 10). Many developing countries have rich natural resources which could be channeled into biotech enterprises with the proper support. For example, in *People's Plants* Ben-Erik Van Wyk and Nigel Gericke outlined over 700 South African plants with economic potential with the specific intent to empower South Africans to use this knowledge to build a bio-based economy.[13] In cases like these, synthetic biology could be used to increase the yield of plant natural products, reduce susceptibility of crops to pathogens, or to develop completely new products that address needs within their local communities.

Table 1 Synthetic Biology's Contribution to the UN 2030 Sustainable Development Goals. The table presents example innovations or scenarios that meet each goal along with potential changes needed within synthetic biology to make these visions a reality.

UN Sustainable Development Goal	Example Innovations/Scenarios	Changes Needed in SynBio Practice
6 Clean water and sanitation	A water filter made of wheat proteins and potato starch incorporates bacterial monooxygenases to remove benzene from contaminated wells after an oil spill	Scale-up lab experiments to ensure real-world application; collaborate with NGOs to identify key toxins
8 Decent work and economic growth	A start-up in Kenya uses synthetic biology to produce a high value compound from an over-harvested plant in the alga *Chlamydomonas reinhardtii*	Collaborate with small-scale farmers and industries to provide education and training; target industrial funding to support start-ups in non-Western countries
9 Industrial innovation	Dyes produced from silica diatom frustles exploit structural color to replace Azo dyes used in the textile industry	Reduce risk; identify key industrial chemicals and dyes that could be replaced by synthetic counterparts
10 Reduced inequalities	Gene synthesis companies automatically apply designated benefit sharing charge for the use of certain genetic materials	Promote access to resources (e.g. gene synthesis, vectors, lab equipment) needed for synthetic biology in non-Western countries; engage with policy makers to develop new policy on the use of organisms and genetic sequences in synthetic biology applications
11 Sustainable cities and communities	Products made using synthetic biology are found in everyday life	Raise public education and awareness of the social benefits of synthetic biology
12 Responsible production and consumption	Industrial chasses use biosynthetic pathways for waste valorization as a source of energy instead of glucose and nitrogen	Reduce the use of plastics and antibiotics; switch to using waste and light for industrial production of recombinant proteins
14 Life below water	Paper-based biosensors based on glutamte sensors from *Bacillus subtilus* detect algal neurotoxins in fish and shellfish to prevent human deaths	Develop new tools to allow for the safe use of bioengineered organisms in the environment to clean up toxins, restore degraded landscapes, and improve agricultural productivity
15 Life on land	Bacteria and plants are engineered to remove polyaromatic hydrocarbons and polychlorinated biphenyls from polluted land	

On the whole, innovations from synthetic biology could lead to the rise of more sustainable cities and communities (Goal 11). In this scenario, low-carbon, degradable, biologically-derived products, from sunscreen and packaging material, would be present in everyday life. Synthetic biology could also contribute to reducing waste within current biotech manufacturing practices (Goal 12). While the amount of plastic waste for industrial manufacturing is unclear, the estimated waste produced by academic science departments lends some insight into this problem. In 2015, researchers from the University of Exeter estimated that 5.5 million tons of plastic were produced annually by 20,500 labs worldwide.[14] Increasing lab access to biodegradable plastics and appropriate methods of disposal (e.g. landfills,

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anaerobic bioreactors) could increase the sustainability of biomanufacturing processes. The overuse of antibiotics within biomanufacturing (as a selection tool for identifying successfully transformed organisms) may also contribute to growing rates of antibiotic resistance.[15] Using chromoproteins as indicators of transformation is one example of a small change in practice that could have wider socio-ecological benefits (reducing the rise of global antimicrobial resistance).[16] Finally, developing industrial chasses that use waste (e.g. lignocellulosic materials) or light for energy would contribute to the development of more circular bioeconomies.[17, 18]

The need for diversity and knowledge exchange

Harnessing synthetic biology to build more sustainable bioeconomies can and should be open to all. However, greater inclusiveness in synthetic biology is needed to achieve this goal. To date, synthetic biology research and industrial innovation has been dominated by the West. Since 1980, 13,050 papers on synthetic biology have been published globally (**Figure 2A**). The majority are from the USA (42%), England (10.5%), Germany (9.4%), and the People's Republic of China (8.7%) (**Figure 2B**). Few are from non-western countries. For example, only 0.19% of papers came from 17 African countries. Recent analysis of synthetic biology industries and research institutes by the Wilson Center also emphasizes the lack of geographic diversity in synthetic biology (**Figure 2C**).[19]

Part of the problem stems from how synthetic biology is funded. Of the 13,050 papers published, most were funded by US, UK and EU institutions such as the National Institute of Health, the National Science Foundation, the National Natural Sciences Foundation of China and the Biotechnology and Biological Sciences Research Council (**Figure 2D**). For synthetic biology to grow in non-Western countries, national governments must commit to funding this research. In addition, charities and national funding agencies that support synthetic biology research (e.g. the development of new vaccines and diagnostic technologies) that aid developing countries, such as the Gates Foundation and the UK Global Challenges Research fund, could earmark funding to support local capacity to do synthetic biology (at the academic or industrial level) in developing countries.

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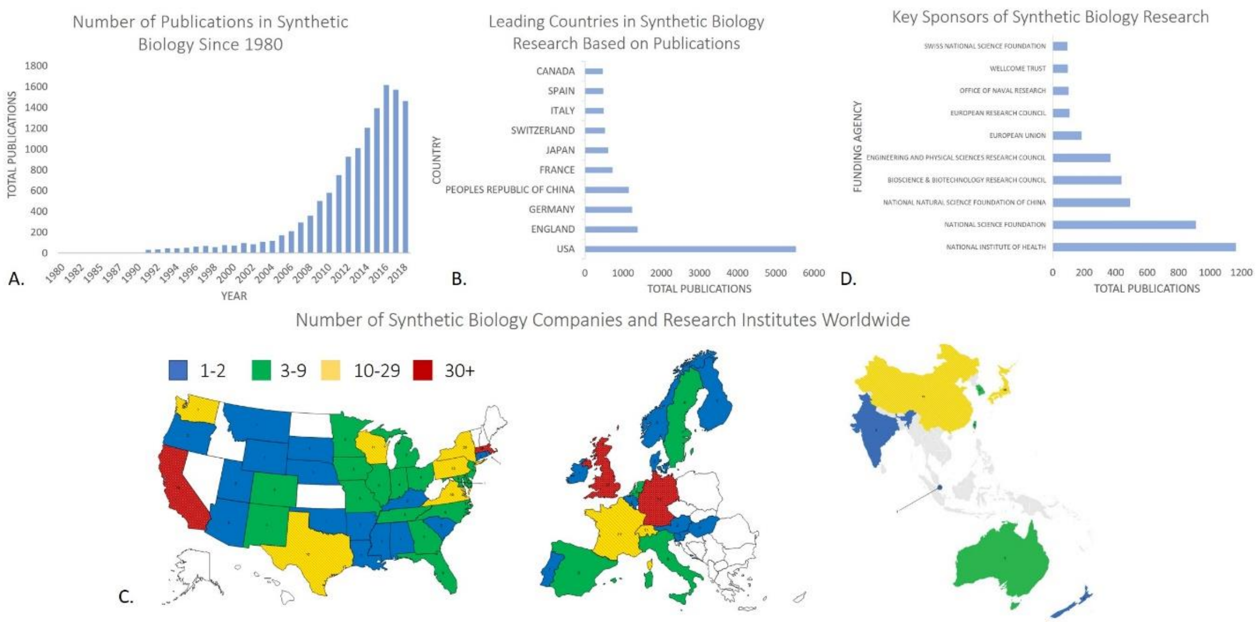

Figure 2 Global overview of synthetic biology research. A. The number of papers in synthetic biology has increased 30-fold since 2000. B. The majority of synthetic biology research is from US, UK and EU countries. C. Geographic distribution of synthetic biology research institutes and companies shows 'hotspots' of activity in Massachusetts and California in the USA, the UK, and Germany. Adapted from ref 19. D. Key sponsors of synthetic biology are Western research and funding institutes. All charts were generated using Web of Science data using the search term "synthetic biology" (Accessed: November 25, 2018).

Increased knowledge exchange could also jump-start bio-based industries in developing economies. This knowledge exchange could be between academics, between academics and local communities, and between industry and non-industrial partners. This would increase local capacity for genetic engineering while supporting the development of local bioeconomies. Activities which could promote such ventures include:

- international exchange programs to promote training in low economic development areas
- providing non-western universities with equipment needed to conduct synthetic biology research
- supporting synthetic biology start-ups through partnerships with established universities or industries.

The University of Cambridge's Open Plant initiative (which promotes sharing tools, resources, and knowledge in plant biotechnology and has provided grants to start synthetic biology labs in Kenya and Nigeria)[20] and the MIT spin out Amino Labs (which produce small, inexpensive, all-in-one kits for doing synthetic biology for schools and researchers in Africa)[21] are good examples of recent work to increase inclusion and diversity in synthetic biology but more work remains to be done.

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Benefits and risk

Synthetic biology could usher in significant changes for the betterment of society: improved sanitation, faster diagnostics, more resilient crops, and new ventures. However, synthetic biology also poses two key risks to establishing more sustainable societies: (1) the exploitation of natural resources from developing countries for commercial gain without ensuring the country of origin for a given resource received compensation and (2) the reduction of global biodiversity through the introduction of genetically modified organisms into the environment as crops, bioremediation tools, or forms of biocontrol.

If left unchecked, synthetic biology-based industries could exploit the genetic resources of non-Western countries by producing synthetic versions of natural products, thereby increasing global inequality. An estimated 7,500 farmers grow *Artemisia annua* in East Africa, 200,000 farmers harvest vanilla (*Vanilla planifolia*) in the tropics, and 3 million farmers grow oil palm (*Elaeis guineensis*) globally, all compounds now produced using synthetic biology.[22,23] The competitive production of steviol glycosides by major chemical companies (e.g. Cargil, Evolva) is a prime example of a synthetic natural product on its way to replacing its living counterpart that has received little attention (**Fig. 3**). The stevia plant was traditionally used by indigenous Guarani people of Brazil; an ethnographer in the early 20th century recorded its use as a sweetener and later it was massed produced in Japan in the 1970s as an alternative to sugar (particularly for diabetics).[24] Today the biosynthetic pathway to produce steviol glycosides is known and there are over 20 patents (many by major food companies) on compounds from the plant and synthetic variations as the market for the sweetener increases.[25] To date, the Guarani people haven't received any benefits from the commercial use of their traditional knowledge and natural resources. Although no synthetically produced versions of natural products have replaced natural versions in recent years (including stevia), the collapse of the indigo market in the early 20th century after the production of synthetic indigo from aniline illustrates that synthetic products can replace their natural counterparts if the market price is significantly lower.[26] Additional quantitative research and data modeling is needed to determine whether synthetic natural products are currently affecting the production, distribution and sale of traditionally produced natural products.

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Figure 3: Commercialization of plant natural products using synthetic biology. Western companies have mass produced synthetic and new-to-nature stevia glycosides for the food and beverage industries. Patenting plant compounds and biosynthetic pathways threatens fair-use of natural resources and the small-scale farmers who grow these plants. All images copyright CCO.

The use of genetically altered organisms could also have a negative impact on global biodiversity in several ways. Genetically altered crops can transfer foreign genes to non-GM varieties and crop wild relatives though wind pollination.[27] In major economic crops like oilseed rape, experimental evidence has shown that foreign genes can spread to plants 2 km away.[28] This could alter plant communities by favoring one species over another and could disrupt the vertebrate and invertebrate food webs in which they are embedded. For example, experimental models suggest that the introduction of genetically modified herbicide-tolerant (GMHT) crops can reduce weed populations and has the potential to greatly reduce the abundance of seed-eating birds.[29] Some research also suggests that genetically modified crops could alter soil microbial communities by shifting microbial community composition in favor of species that can metabolize root exudates from genetically-modified plants.[30] Recent advances in genetic engineering, namely gene drives, have also greatly enhanced our ability to affect wider, more diverse populations of wild organisms. Such drives use Crispr/cas9 systems to self-replicate through a population, eliminating key genes involved in fertility and reproduction along the way.[31,32] This technology has the potential to eradicate pests that cause disease (e.g. malaria, Dengue) and damage crops (e.g. locusts, rats).[33] However, eliminating wild organisms considered “pests” using gene drives could also disrupt local food chains in unforeseen ways or reduce populations of the targeted species in areas where they are not causing harm to human welfare.[34,35]

The risks from synthetic biology should not present a barrier to the use of these technologies to achieve sustainability goals. Instead, these risks should be identified and mitigated. Within the field of synthetic biology there is a strong commitment in developing containment systems for genetically modified organisms. These include insertion of foreign genes into organelle genomes,[36] the dependence of engineered organisms on supplied nutrients for survival (e.g. unnatural amino acids),[37] the introduction of 'kill-switches' to immediately remove engineered organisms from the environment,[38] and the use of localized (as opposed to global) gene drives that successively lose power with over time (daisy-chain drives).[32, 39, 40]

Legislation touching upon many aspects of synthetic biology—from organism engineering to field trials--is also growing and have been extensively reviewed elsewhere.[41-43] For example, the Nagoya Protocol regulates the use of digital genetic sequence data while national governments regulate the release of genetically modified crops and other organisms into the environment. In 2018, the IUCN developed a task force to address the above issues (the use of digital sequence data, natural resources and release of genetically modified organisms into the environment, all in regards to their impact on global biodiversity) which may provide new opportunities to strengthen policies around the above issues.[44] Potential amendments could include:

- the introduction of a ban on the production of compounds from certain rare or nationally significant organisms
- instigating a specific 'tax' on the use of genes which come from a list of priority or protected organisms
- developing new risk assessments and GIS platforms integrating biological and environmental data to evaluate the potential benefits and damages of using modified plants and other organisms in a given area
- implementing changes to the Nagoya protocol that mandate biotech companies focusing on natural resources have an Ethics officer to handle issues of intellectual property and genetic resources
- developing new national approval processes for bio-based products which must be approved and certified by a centralized regulating authority to ensure fair-use policies and benefit agreements found in agreements like the Nagoya Protocol are upheld

Such changes, although small, could ensure all nations reap the benefits of synthetic biology with minimal harm to the availability and quality of national natural resources and ecosystem services.

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The challenge

We have just over a decade to reach the UN's 2030 Sustainable Development Goals. If synthetic biology will play a part in reaching them, significant changes will need to be made to synthetic biology as a technology and as a means to drive, possibly ground breaking, social change. At the moment, synthetic biology is confined to academic labs and startups. Less than 70 synthetic biology-derived products are on the market worldwide.[45] The greatest challenges to widespread adoption of bioinspired materials and services in everyday life will be barriers to scaling up (which include lack of start-up funding and technological challenges such as reproducibility and uniformity of biological materials), regulation around the use of genetic materials in the natural environment, public acceptance of these innovations, and ensuring fairness, inclusion and opportunity in synthetic biology as the field rapidly advances and the gap between Western and non-Western technology widens. Synthetic biologists will need to capture the imagination of the general public and the support of policy makers in order to make this vision for a more sustainable future a reality.

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