THE FUTURE OF THE WESTERN CAPE AGRICULTURAL SECTOR IN THE CONTEXT OF THE 4TH INDUSTRIAL REVOLUTION

Review: Synthetic Biology

October 2017

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University of Stellenbosch Business School

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1. Technology Overview and Detailed Description

Synthetic Biology (SB) is the design of biological systems and living organisms using engineering principles, with the objectives of (1) contributing to basic research on the fundamental mechanisms of life itself (2) deploying biology as a technology for constructive purposes and (3) extending or modifying the behavior of organisms and engineer them to perform new tasks [1,2,3]. In achieving its objectives, SB combines scientific disciplines and is generally understood to involve the deliberate design of biological systems, using standardized components that have been created in a laboratory[4]

SB goes beyond the transfer of pre-existing individual genes, encompassing a broader range of genetic engineering strategies, from the tinkering of the genetic code itself to the complete synthesis of microorganisms, including the design of novel proteins and metabolic pathway engineering. Depending on their specific objectives, the engineering effort of SB projects may focus on different scales: DNA regulatory elements, genes/proteins, genetic circuits and metabolic pathways, whole genomes, cells or even larger systems such as microbial consortia[5]. Two different approaches may be distinguished: the modification of existing cells, or the complete construction of artificial systems.

The major enabling technologies are (i) DNA synthesis (a topic covered elsewhere in another report in this project), (ii) and DNA sequencing (iii) DNA amplification (iv) computational modelling (iv) reconstruction and (v) the ability to model and design genetic circuits and metabolic pathways, and (vi) measurement[6].

2 Application Examples and Case Studies

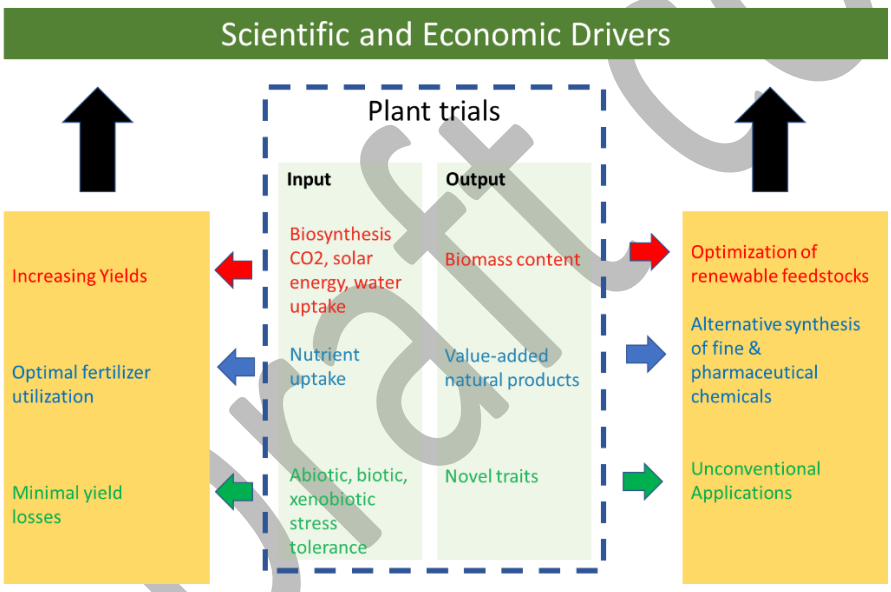
Agriculture applications

SB has been successfully applied in plant breeding through metabolic engineering for better nutritional value or for economical alternatives in agriculture production. For example, metabolic engineering has been applied to the production of vegetable oil containing the omega-3 polyunsaturated fatty acids docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). These fatty acids are essential for human health, especially for the inflammatory response and for brain development. They are naturally found in fish through their plankton diet.

Metabolic engineering enabled the heterologous production of such plankton products in soybean. The resulting soybean plants should alleviate the need for catching wild fish as feed for aquaculture and may provide a direct vegetable source of valuable fatty acids for human diet[7], or as an alternative feed source, significantly reduce the cost of feed.

Artificial plant mini-chromosomes have been proposed and engineered to facilitate the transformation of sets of genes in plants in one step and without interfering with the plant genome[8], however in so doing, ethical issues will need to be taken into account, guided by policy.

With respect to arable and horticultural production, it would seem unlikely that SB will result in any significant shift in consumer acceptance of engineered crops destined for the food chain. Rather, the initial potential for SB in plant biotechnological applications lies in engineering input and output traits in non-food crops and potentially even in generating wholly new plant varieties/species for specialized chemical and biomaterial production. Indeed, the generation of specialist 'industrial' plants which can be separated from crops destined for the food chain at the point of harvest and processing would seem to be a vital prerequisite to fully realize the potential of genetic and SB engineering of feedstocks for efficient biorefining and other industrial applications. Some of the promising targets for SB-based engineering of input and output traits are shown in Figure 1 below.



SB and input traits

Figure 1: Proposed targets for the engineering of input and output traits in plants using SB[9].

SB has been used to study photosynthetic re-engineering, carbon fixation, nitrogen fixation to maximise the conversion efficiencies of solar to biomass[10,11,12,13].

In addition to nutrient input traits, SB has the potential to provide crop science with new traits to offset the increasing diversity of abiotic (environment), biotic (pathogens, herbivores), and xenobiotic (pollutants) stress which are now affecting agriculture. SB could provide a route to

greater resilience in agriculture faced with an increasingly extreme and variable climate and associated pressures resulting from invasive pests and diseases.

The ability to precisely engineer plant genomes with the aid of synthetic site-specific nucleases has recently been shown to be very successful in designing plants tolerant to biotic and abiotic stresses[14]. These site-specific 'genome editing' advanced techniques include transcription activator-like effector nucleases and zinc-finger nucleases. Applications include the selective engineering of resistance to *Xanthomonas oryzae* in rice[15] and tolerance to imidazolinone and sulphonylurea herbicides in tobacco[16]. These tools are also proving useful in generating designer genomes for further metabolic engineering, as demonstrated by the introduction of regularly interspaced short palindromic repeats (CRISPR) in rice and wheat[17].

SB and output traits

Output traits of interest to biorefining applications include the rational construction of crops that produce high yields of useful intermediates, which can then be readily used by existing chemical industries, requiring lower inputs of energy and materials in their processing and with a usable set of by-products to facilitate the move towards zero waste refining. The latter is an important point when introducing a disruptive technology in competition to the well-established and highly efficient oil-refining industry.

Linking photosynthesis to a synthetic pathway to butanol production by direct coupling to the Calvin cycle (a biochemical cycle in cells) to facilitate synthesis of butanol (a valuable biofuel) and industrial intermediate[18] is an example of such an application of SB.

Applications in fundamental agricultural sciences

Applications of SB can be extended to the understanding of fundamental science. Examples are discussed below.

a. Microbial synthesis

Scientists produced and assembled the first synthetic bacterial genome, *Mycoplasma genitalium*, a circular chromosome of over 580 kilobases of DNA[19] . As a step toward testing and propagating synthetic genomes, they also managed to fully replace the genome of a bacterial cell with one from another species by transplanting the whole genome as virtually naked DNA[20].

b. Redesigning essential functions in simplified or minimal genomes

Three main approaches are being taken around the world to understand what are the minimum functions required in a reconstructed cell, for life. These are comparative genomics, genetic knock-outs, or biochemical approaches[21]. Most of the research has been carried out on bacteria in which genes are progressively eliminated, so revealing those which are essential to life and those which are not. Early estimates put the minimum required number at 500–800 genes, but subsequent work has suggested that it may be as low as 300–400. Using this knowledge, it becomes possible to design and build cell factories, the output of which will depend on what additional genes are added to the minimal set required simply to sustain the organism's existence. A full knowledge of which genes are essential to do what also helps the bioengineer not only to create new and specialised organisms by eliminating unwanted genes, but to build novel organisms from scratch[22].

Other laboratories attempt to simplify the unnecessary complexity of natural metabolic pathways using existing or synthetic metabolic shortcuts by metabolic engineering. For example, the complex biosynthesis of deoxyribonucleotides constituting DNA has been successfully replaced by a simpler and more efficient pathway, starting from gluconate and using a combination of two enzymes functionally adapted by directed evolution[23].

c. SB has been used in industrial applications for bioenergy and biomaterials. The rational design and directed evolution of metabolic pathways have led to the production of alternative non-natural biofuels[24]. For example, Liao's laboratory designed a biosynthetic metabolic pathway to produce C4 and C5 alcohols in *E. coli* by combining novel enzymes engineered to elongate alcohols and to adopt novel substrate specificity[25].

d. Another contribution of SB to the use of biomass for biofuel is through the design of enzymes with improved performance to degrade cellulose. As a recent example, fungal cellulases have been designed with improved thermostability through modelling and structure-guided recombination. Using a computer software, the sequences of three known fungal cellulases were "mated" to make more than 6,000 progeny sequences, different from the parents but encoding proteins with the same structure and cellulose-degradation ability. By analyzing the enzymes encoded by a small subset of those sequences, the researchers could predict which of the more than 6,000 possible new enzymes would be the most thermostable. Using the computer-generated sequences, they synthesized novel DNA molecules, and transferred them into yeast. The yeast produced the enzymes, which were then tested for their cellulose-degrading ability and efficiency. Each of the 15 new cellulases reported in the paper was more stable, worked at significantly higher temperatures, and degraded more cellulose than the parent enzymes at those temperatures[26].

e. The natural activity of cells is controlled by circuits of genes analogous to electronic circuits. So another approach to making cells do new things relies on creating novel internal circuitry to alter their pattern of activity. Using well-understood genetic components that act as molecular switches it should be possible to devise artificial gene networks. Linked together and implanted into natural systems such networks could be used to control what those systems do, when, and how frequently. Integrated into suitable cells an artificial network might be used to sense and correct metabolic disturbances of the kind found in diabetes[27].

f. SB is also applied to the production of biomaterials, producing novel chemical precursors of plastics and textiles.

g. SB finds many applications in the design of sensors, (for surveillance and remediation) and environmental sensors. SB technology has been demonstrated using plants in new biomonitoring applications to detect chemicals (e.g. pollutants, explosives) or pathogens as well as bioremediators. Plants have an innate ability to continuously sense and respond to the environment using signal transduction systems based on the recognition of small molecules. By introducing new sensor or reporter systems, these responsive signalling networks could be adapted using SB to provide new functionalities for sophisticated and low-cost applications in environmental detection. These first prototype detector plants have the potential to detect foreign compounds in soil as well as in air, allowing their potential use in a variety of remediation and security applications[28].

h. One of the best-known examples of SB is the production (up to 100 mg l^{-1}) of the sesquiterpenoid artemisinic acid in yeast, with the derived compound artemisinin a drug used in the treatment of malaria. Genes taken from the medicinal plant *Artemesia annua* (the natural source of artemisinin) and *Escherichia coli* were used to re-programme the host's metabolism to efficiently provide terpene precursors[29]. The approach developed to support large-scale artemisic acid biogenesis was then adapted to produce other members of the isoprenoid family, which represents some 50 000 different types of molecules with a wide diversity of potential applications, including uses as pharmaceuticals, flavour and fragrance compounds, and fuels.

By switching a single enzyme in the artimisic acid biosynthesis pathway of the engineered yeast, the associated pathway was switched from producing a pharmaceutical intermediate to the biofuel precursor farnesene[30].

Other possible uses of SB include the following:
Energy - Custom-built microbes for generating hydrogen and other fuels, or for performing artificial photosynthesis;

Medicine - The manufacture of drugs, vaccines and diagnostic agents, and the creation of new tissue;
Environment - The detection of pollutants, and their breakdown or removal from the environment;
Chemical industry - The production of fine or bulk chemicals, including proteins to provide an alternative to natural fibres or existing synthetic fibres;

Whilst most SB technologies will be fully commercialized in a decade or so, some inventions have already been commercialised. A selection from 200 companies in this space is given below in Table 1 below to give the reader a sense of the extent of commercialization.

Table 1: A selection of companies involved in the commercialization of SB technologies (reproduced from publication by the Royal Academy of Engineering[31])

	Company	General area of SB	Description
USA, California	Amyris Biotechnologies	Drug Development and Biofuels	Amyris Biotechnologies is a spinout of UC Berkeley. Its primary role is to exploit the work of Professor Jay Keasling's laboratory in the development of a synthetic anti-malarial drug called artemisinin. The company is also developing several biofuels, including a biologically based aviation fuel.
	LS9	Biofuels	LS9 are developing a range of **biofuels** produced by specially engineered microbes created via industrial SB. It is intended that these DesignerBiofuels™ will be cost-competitive with traditional petroleum products and be commercially available within a few years
	Synthetic Genomics	Energy and environment	Synthetic Genomics are seeking novel genomic-driven strategies to address global energy and environmental challenges. They are using recent advances in the field of synthetic genomics to develop applications to produce energy, chemicals and pharmaceuticals and to enable carbon sequestration and environmental remediation.
	DNA2.0	Gene synthesis	DNA2.0 is a synthetic genomics company and one of the largest US providers of synthetic genes. They offer a number of services including gene synthesis, bioinformatics software, codon and amino acid reference tools, and a literature database.
USA, Massachusetts	GreenFuel Technologies Corporation	Biofuels	GreenFuel's high yield alg**ae farms recycle carbon dioxide from flue gases to produce biofuels and feed**, reducing net carbon dioxide production as waste becomes profit. **Harvesting algae for biofuels** enhances domestic fuel production while mitigating CO_2.
	Mascoma Corporation	Agriculture and energy	Mascoma's R&D team is focused on developing **biofuels from non-food biomass wood, straws, fuel energy crops, paper pulp and other agricultural waste products**. Their research laboratories are now developing a new generation of microbes and processes for economic conversion of cellulosic feedstocks into ethanol.

	Company	General area of SB	Description
	New England BioLabs	Production and supply of reagents for the life science	Established in the mid-1970s as a cooperative laboratory of experienced scientists, New England Biolabs focus on the production and supply of reagents for the life science industry. They now offer one of the largest selections of recombinant and native enzymes for genomic research and are expanding their products into areas related to proteomics and drug discovery
Rest of United States	Blue Heron (Washington)	Gene synthesis	Blue Heron is a leader in gene synthesis. Their GeneMaker® technology can produce DNA sequences from 60 base pairs to well over 20,000 base pairs in length including the first synthetic DNA fragment over 50,000 base pairs. Their Expression Optimization and Codon Optimization services also offer the flexibility to design DNA sequences for various expression systems or future sub-cloning manipulations.
	Genscript (New Jersey)	Pharmaceuticals and biotechnology	GenScript is a biology Clinical Research Organization that focuses on early drug discovery and development services. Built on their assembly-line mode solution, GenScript provide a range of services that include Bio-Reagent, Bio-Assay, Lead Optimization, and Antibody Drug Development
	Scarab Genomics (Wisconsin)	Clean genome *E. coli*	Scarab Genomics has bioengineered the Clean Genome® *E. coli* by deleting over 15% of the genome. Genome reduction optimizes the E. coli as a biological factory and makes the Clean Genome® *E. coli* a popular strain for a wide spectrum of applications ranging from routine cloning to production of biopharmaceuticals.
	Gevo (Colorado)	Biofuels	Gevo are developing **next generation biofuels** such as butanol by engineering suitable host organisms that utilize carbon and energy efficiently for fuel production. They have also developed a proprietary process to convert agricultural waste products into different types of renewable, alcohol-based, liquid fuels.
	Chromatin Inc (Illinois)	Agriculture	Chromatin Inc has patented mini-chromosome technologies that enable the development of **new seed products and the delivery of multiple genetic traits** in plant systems. The application of this technology will allow agriculture companies to develop new seed products with applications, primarily in **biofuel feedstocks and optimised food production**
Europe and the rest of the world	ProtoLife (Italy)	Modelling technology	As the amount of data generated using high-throughput experiments in SB increases, analysis becomes ever more difficult. To address this issue, ProtoLife have developed Predictive Design Technology™ (PDT), an automated, intelligent predictive modelling tool that finds optimal targets in huge, complex experimental spaces without exhaustive screening.

Company	General area of SB	Description
BP (Global)	Biofuels	An important component of BP's activity in SB comprises partnering with Synthetic Genomics. The initial phase of the BP/Synthetic Genomics project will focus on identifying and describing the naturally occurring organisms and their natural biological functions that thrive in subsurface hydrocarbon formations. The main goal is to explore and understand subsurface microbial processes. Such an understanding would enable **hydrocarbon quality enhancement** or increased production. BP and Synthetic Genomics will seek to jointly commercialize the bioconversion of subsurface hydrocarbons into cleaner energy products. The second phase of the BP/Synthetic Genomics program will be a series of field pilot studies of the most promising bio-conversion approaches.
GENEART (Germany)	Gene synthesis	GENEART is a company which specialises in SB. They supply a wide range of businesses such as pharmaceutical & biotechnology companies and the chemical industry as well as academia. Their services include the production of synthetic genes, the generation of gene variants, gene libraries in combinatorial biology and the production of plasmid DNA
DSM (The Netherlands)	General	DSM is active in the field of SB across a wide range of products and services including nutritional and pharmaceutical ingredients, performance materials and industrial chemicals.
Genencor (Denmark)	Agriculture and food	Genencor is a Division of Danisco, are involved in gene expression, protein chemistry, protein engineering, expression and secretion, and immunology.
Bioneer (South Korea)	DNA Purification	Bioneer is a privately held biotechnology company based in South Korea. Its core business is to provide total genomic research solutions ranging from reagents to state-of-the-art instruments used in molecular biology.

Notes: Emphasis in **bold** is that of the author

The reader is directed to more reviews on the application of SB in the literature[32]. Furthermore, a brief history of synthetic has been well documented with illustrations[33], and the reader is referred to this publication for the details

3. Technology or Application Life Cycle: Current Status and Expected Development in 2020 and 2050

Table 2: Life Cycle

Technology Area	Current application in agriculture	Expected applications in agriculture by 2020	Expected applications in agriculture by 2050
SB	Biomass yield increase (although still sub-optimal).	New crops with desirable traits such as salt-tolerance, drought-tolerance, and pest-resistance;	Man-made cells that are capable of self-assembly and self-repair and able to reproduce.
	Speciality chemicals synthesis.	Potential to produce different kinds of food, including meat and drinks at lower costs than today. By manipulating genes, brand-new foods can be created with new properties or flavours.	Synthesis of micro-organisms with novel traits. Design of novel input and output plant traits.
	Biosensor applications, biomaterials, plastics and textiles.	Development of new gene-delivery technologies will enable the development of new seed products with multiple genetic traits.	Integration of novel feedstocks with novel processes development of enzymes which can break down a much wider range of biomass into useful forms.
	Multi-enzyme pathways for the *in vitro* production of complex fine chemicals such as unnatural monosaccharides for the pharmaceutical industry	New types of pesticides which are environmentally friendly optimisation of seed stocks to produce effective crops in difficult and complex environmental conditions, such as climate change	Development of plants whose whole biomass is readily convertible. Reduction of CO2 levels by the development of artificial leaf technology.

4. Business Eco-System View

SB overlaps with the following technologies:

- Genetics

- Bioinformatics
- Biorefinery and biofuels

5. Benefits and Risks

The literature[34] cites the following as the benefits and risks of SB, in particular the effects on biodiversity.

Table 3: Benefits and Risks

Benefits	Risks
Reduce the impact of human land use on biodiversity, by, for example, reducing the need for pesticide use (which can have negative impacts on non-target wildlife)	Transfer of genetic material to wild populations is a major risk (Genetically engineered microbes could have adverse effects in the environment due to their potential to persist and transfer their genetic material to other microorganisms)
New methods of energy production, such as algae that use carbon to produce fuel	Lead to a loss of genetic diversity and the spread of harmful characteristics. Even without genetic transfer, these organisms could have toxic effects on other organisms such as soil microbes, insects, plants and animals. They may also become invasive.
Bioremediation could benefit biodiversity. Bacteria such as Rhodococcus and Pseudomonas naturally consume and breakdown petroleum into less toxic by-products. Synthetically engineered microbes could be used to degrade more persistent chemicals such as dioxins, pharmaceuticals, pesticides or radioactive substances (which might otherwise be sent to hazardous waste landfills).	Introducing new diseases by replacing the population of the original disease vector with another
Synthesise products currently extracted from plants and animals. Engineering biosynthetic pathways provides an alternative and cost-effective method of producing drugs of natural origin, such as morphine and aspirin	Potential to disrupt conservation projects and displace small-scale farmers due to the ability to replace natural products with synthetic products
Restore genetic diversity and even extinct species has been widely reported, using SB to re-create extinct species	Large-scale increase in the use of biomass as feedstock for SB processes could reduce soil fertility due to extraction of this biomass from the natural environment
protecting at-risk species by genetically modifying bees to be resistant to pesticides or mites for example	Land-use changes may also have adverse impacts on food (traditional crops) and livelihood security, due to small farms being acquired for large-scale commercial operations
Control of disease vectors. Using gene drive systems, it is possible to change the genomes of populations of mosquitoes to make them less	

Benefits	Risks
dangerous (e.g. resistant to the parasite that causes malaria)	
Invasive species may be eradicated through the application of gene drives in their populations.	

6. Potential Economic, Social, Ecological (Environmental) and Political Developments and Impacts

Economic Developments and Impacts

- The global market for SB products is growing rapidly, as are investments in SB research. The global SB market is expected to grow to $11.8 billion in 2018. While smaller than the estimated global market for nanotechnology ($20.1 billion in 2011, $48.9 billion in 2017), SB's predicted compound annual growth rate of 45.8% outshines nanotechnology's 18.7%[35]. The US and European governments funded over a half billion USD in SB research between 2005 and 2010[36].
- Products from SB, such as artemisinin, may improve the health of the people of developing countries and thus their economies.
- SB alternatives to natural products may lead to product displacement, harming the economies of developing countries and displacing the livelihoods of small-scale farmers and pickers.
- The necessary scale of extraction and use of biomass for a global economy may be ecologically unsustainable and rely on the same biomass resources as traditional economies.

Social Developments and Impacts

Advances in SB have resulted in ethical and societal impacts. The key concerns are:

- Safety and (bio-)security concern, based on the perceived risk of harmful organisms (for example engineered viruses) being released, either deliberately or accidentally, into the environment. Literature recommending the application of intrinsic biocontainment provides some solutions to allay this concern[37],[38]
- Issues surrounding intellectual property rights, and scope of claims which must be controlled and insulated from multinational companies seeking to inhibit development through the pursuit of revenues,
- Ethics considerations pertaining to the creation of new life forms

- Inappropriate access without benefit sharing due to the use of sequenced data without material transfer agreements under the Nagoya Protocol.
- Indigenous peoples and local communities will not necessarily support or benefit from the utilization of genetic resources in SB.

Ecological (Environmental) Developments and Impacts

SB applications could also have indirect negative impacts on the conservation and sustainable use of biodiversity arising from a large-scale increase in the utilization of biomass. Specific examples of this are presented in Section 3.5 above (Benefits and Risks), and will not be repeated here.

Political Developments and Impacts

- Effects of SB on developing countries - SB is likely to have significant effects on the cost benefit analyses of a variety of actors in the international economy. Technological improvements change the cost-benefit analysis of a variety of producers along the supply chain, and some of these producers will have more difficultly adapting old modes of production than others.
- The inability to adjust can lower existing firms' profits, as old technologies obsolesce and new technologies gain market share. If these profits are lowered to unsustainable levels, firms will be priced out of the market.
- Exports from oil-rich countries may be threatened when biofuels production is able to replace oil-derived fuels.
- The conversion of food crops to fuel production has the potential to significantly increase the cost of staple food products and exacerbate concerns about continuing food crises.
- Successful adaptation to new technologies requires national governments to reconsider their areas of comparative advantage, pursue new types of industrial policies, and create environments conducive to entrepreneurial behaviour. Developing countries, however, do not always have the capacity to facilitate effective research or industrial restructuring; in these cases, the social impact of technological change is more severe.

Annexure 1 illustrates the alignment of SB with the key policy mandates of DAFF, articulated in the NDP, and APAP, and illustrates where SB and possibly technologies of the future may be used to support the delivery of the South African government's proposed interventions as articulated in the APAP.

SB in Africa

There are factors that have delayed the development and application of biotechnology in many countries of Africa, in comparison to the rest of the world. These are listed below:

- The absence of clear priorities and investment strategies - most African countries do not have clearly identified investment strategies identified specific areas or technological trajectories in which to invest to meet specific goals[39].
- The application of short-term and low-level financing of biotechnology R&D in many African countries (less than US$250,000 per year, the exceptions being Egypt, Mauritius and South Africa), in biotechnology has resulted in African countries stretching their financial and human resources across biotechnology sectors and research agencies, and other department priorities, especially development[40].
- Intellectual property protection - in most African countries institutions/regulatory are not well established. As such opportunities to develop and protect new inventions are missed[41]
- In most developing African countries, critical scientific mass, basic infrastructure and facilities, as well modern communication systems, power supply and chemicals and consumables for research are either lacking, in short supply, or are unreliable[42].

7. Conclusions

The Royal Academy of Engineering[43] has made recommendations to the UK academic and industrial sectors with respect to SB. These are summarized below, and can be implemented in any region wishing to exploit the benefits of SB.

a. Governments are to develop a national strategy on SB, which includes disciplines such as engineering, life sciences, physical sciences, and the social sciences;

b. Stakeholder engagement should be a strong feature of a national strategy, between industry and academia, to facilitate the commercialization of intellectual property;

c. SB centres should be located within leading, already-active universities that have internationally competitive research in engineering and the physical sciences, and biology, seeking to become, and remain multidisciplinary;

d. Recommended areas of research are: 4.1) physiological differences between natural and synthetic organisms; 4.2) study how engineered microorganisms might alter habitats, food webs or biodiversity; 4.3) determine the rate at which synthetic organisms evolve and whether they could persist, spread or alter their behaviour in natural environments; 4.4)

study gene transfer by synthetic organisms (for example, whether synthetic organisms could transfer antibiotic resistance)[44];

e. A critical mass in terms of researchers, facilities and equipment, based at an SB centre, should be adequately funded over a long period. The recommended funding in the UK was £ 60m over a 10- year period;

f. SB research should be undertaken with social scientists and philosophers to raise awareness of the ethical and societal issues, and should also involve policy-makers, industrialists and regulators.

8. Synthesis and key trends from the literature

a. SB is a new and exciting technology. The new science of SB promises a step change in our power to shape life. Using this new technology, it is possible to engineer life from the ground up allowing the formation of organisms with genetic code not found in the natural world. The technology is still in its infancy and arguably a few years behind Nanotechnology. However, there are some commercial examples and growth can be expected over the next 10 years.

b. Scarcity trends will drive innovation. There are 850 million undernourished people in a world with a population growing at more than 6 million per month. Already over 50% of people live in urban dwellings and estimates suggest this will rise to 60% by 2050 when the population will reach 9 billion. Many believe that SB will be one of the transformative technologies necessary to combat climate change, energy shortages, food security issues and water deficits. By rewriting the genetic code, it may be possible to make plants disease resistant, and salt, heat and drought tolerant. The cost of large scale biofuel production and some medicines could be reduced as engineered bacteria produce the raw materials.

c. Need for harmonization of regulation. There are differences in the regulatory approach to traditional genetically modified crops and animals across the world. Furthermore, there is no consistent global view on the appropriate approach to regulating SB, and there is a concern that current regulations are too disjoint to manage the risks of these novel technologies; public opinion on the use of this technology appears to differ regionally. Within regions it is typical that there are several agencies with potential jurisdiction over processes using the new methods. A single body could be set up in each region to oversee and coordinate the approach and to aim for global consistency, as with nanotechnology in the USA). Global consistency on: monitoring, assessing risk, tracking use and labelling of products would be desirable.

d. Valid concerns and address. Besides the concern that access to technologies could fuel "bioterror" there are also concerns around "bioerror", i.e. the accidental release of synthetically engineered organisms that could lead to environmental or health problems, due to ecosystem effects such as unexpected gene transfer between GM crops and their nearby natural neighbours.

e. Debate amongst key stakeholders. Focus groups involving the public (including a variety of religious views), biotech industry, security advisors, developing countries, governments/regulators, insurers and research scientists should be established to encourage debate.

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