Education and training for industrial biotechnology and engineering biology

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Abstract: Industrial biotechnology is focused on the production of bio-based fuels, chemicals and materials such as plastics and textiles. Engineering biology, synonymous with synthetic biology, provides a platform technology that brings an engineering approach to harnessing biotechnology for industrial production. The two combine within the political construct of the future bioeconomy, in which bio-based gradually replaces fossil-based production. There are many barriers to this future, including technical, political and social aspects. Behind all of these is a need for a new form of workforce not seen before, in which various skills and knowledge bases merge and combine. The required multi- and interdisciplinary skills challenge higher education to get out of the discipline-dominated paradigm. This study examines some of the current and future critical issues and provides some examples of how higher education is rising to the challenge.

1 Introduction

Organisation for Economic Cooperation and Development (OECD) analysis suggests that innovation thrives in an environment characterised by a few key features, including a skilled workforce [1]. Skills will be central to enabling bio-production due to the newness of the subject, its multidisciplinary 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.

Industrial biotechnology includes the manufacture of biofuels, enzymes, and bio-based chemicals and materials. A key discipline of industrial biotechnology is microbiology. Life sciences PhD-level education remains focused on training for academic careers [2]. However, data from 2010 published in the National Science Board 2014 Science and Engineering Indicators show that a mere 29% of newly graduated life science PhDs will find a full-time job openings [4]. There are simply too many PhD students and too few senior positions [5].

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 [6]. 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 [7]. This has all brought about a call for a new type of PhD, one that offers much more breadth and flexibility.

2 Challenge of multi- and interdisciplinary education

Traditional scientific education and training has remained divided by disciplines such as microbiology, chemistry and computing. The long-standing conundrum of multidisciplinary 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- and interdisciplinary as some of the depth skills needed are systems thinking, strategic planning, and evaluating environmental, social and economic performance. This educational conundrum for sustainability [8] is the same for industrial biotechnology and engineering biology: how to make the interdisciplinary approach not only substantive but also practical for early-career scientists.

3 Life sciences industry-wide issues

Some of the life sciences-wide industry issues are clearly crystallised in an American report [9]. 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.

Fig. 1 Likelihood to work in academia for newly graduated PhDs (per cent)

The low figures for engineering and computer sciences reflect the greater likelihood that these PhD graduates will enter industry
4 Critical workforce gaps in bio-based manufacturing

Industrial biotechnology is the fastest growing subsector of biotechnology ahead of biologics and genetic modification (GM) crops [11]. However, this burgeoning industry is faced with skills gaps. Finding biologists is not the most difficult task for employers. Automation engineers specialising in high-throughput strain production critical to engineering biology-based manufacturing are rare. Managing automated systems will have to be a skill set for graduates in biology and chemistry in the future [12]. We see the reality of this hitting soon with the large sums being raised by companies like Zymergen and Ginkgo Bioworks, the latter now valued at an estimated $1.3 billion. 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. 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 [13]. Big data is creating an imperative for more complex design that enables fewer sets are becoming more common [13]. Big data is creating an imperative for more complex design that enables fewer.

5.1 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 [22].

6 Synthetic biology education: another key interdisciplinary

The education system has been responding to the needs of the growing synthetic biology community. The number of courses in synthetic biology has grown rapidly, with at least 100 institutions involved [23]. However, many do not focus on industrial production. Therefore, industrial biotechnology courses, and organisations teaching them, are still very much pioneers.

7 Beyond science and engineering

Given the history of the GM debate, such matters as public perception will also shadow industrial biotechnology and engineering biology. There is already evidence that political and economic pressures will guide development of engineering biology [24]. Kuldell [25] 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 engineering biology and industrial biotechnology more broadly. Public engagement is weakened by a lack of a standard approach [26]. 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 [27].

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.
Some approaches to industrial biotechnology and engineering biology education and training

The US National Science Foundation (NSF) Center for Biorenewable Chemicals, a third-generation Engineering Research Center (ERC) established at Iowa State University in 2008, is currently a partnership between eight United States and four foreign institutions [29]. 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 [30]. It offers courses for school teachers, through undergraduate and graduate education.

8.1 Undergraduate courses: preparing the way

It is probably too early for full 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 quantitative skills that are important for success in industry. Students so equipped with skills in calculus, linear algebra, statistics, large dataset management and programming would be better prepared for future education in, and a career based on, engineering biology [2].

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 bio-materials 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, or the manufacturing of safe food products.

8.2 Taught and research masters

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.

The University of Georgia Master of Biomaterial and Bioprocessing degree, a 2-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/biochemicals, pharmaceuticals manufacture) and business (e.g. finance, supply chain issues and manufacturing practices). Instead of producing a traditional thesis, students complete a research project resulting from a 400-h industry internship.

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 in order to develop advanced mathematical models for chemical and biotechnological processes.

8.3 Training PhD students in interdisciplinarity

The United States NSF had a flagship interdisciplinary training programme at North Carolina State University – the Integrative Graduate Education and Research Trainingship (IGERT), educating PhD scientists and engineers by building on the foundations of their disciplinary knowledge with interdisciplinary training. Since 1998, the IGERT programme has made 278 awards and has provided funding for ~6500 graduate students.

Research topics were selected specifically to transcend traditional disciplinary boundaries and so encourage teamwork. Diversity in the background of selected students was a factor in their preparation to solve large and complex research problems of significant scientific and societal importance – typical of the so-called grand challenges that engineering biology is supposed to be able to address. Insights from IGERT are provided by a personal communication from Professor Fred Gould (Box 1).

8.4 Massive Open Online Courses

The traditional on-campus experience could be radically changed by Massive Open Online Courses (MOOCs), which will enhance classroom and laboratory work. The evidence for the impact of MOOCs is still embryonic, although in the United States drop-out rates are remarkably high and accreditations are as yet negligible [31]. More analysis is needed as greater experience is acquired with their use. A number of MOOC platforms, such as Coursera [32] and edX [33], now provide 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 2).

MOOCs are easily scalable and adaptable, which are important benefits. Industrial biotechnology and engineering biology are expanding and changing rapidly. As a result, educational materials can quickly 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. Inevitably hybrid approaches that have elements of the MOOC approach will emerge. For example, SynBio4All, being developed at the Centre de Recherches Interdisciplinaires in Paris, can be described as part MOOC, part open laboratory notebook, and part crowdsourcing discussion platform on synthetic biology [35].

8.5 Specialist training facilities

For early-career scientists, gaining access to bio-based production experience is difficult because universities do not normally have the relevant facilities. The National Institutes model in Ireland 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 [36]. The institute builds

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Box 1. Impact of interdisciplinary training on disciplinary depth at NSF-IGERT

“Our NSF-IGERT graduate training programme was titled ‘Genetic Engineering and Society: The case of transgenic pests.’ Our vision for the programme was development of ‘a group of interactive students, trained in technologies used for manipulation of pest genomes as well as methods needed to assess the environmental and socio-cultural appropriateness of specific products of these manipulations.’ 

When we first started the programme, some faculties were reluctant to have their students participate because they felt that such broadly trained PhD students would not have the depth in a single field that would be attractive to academic and industry employers. The Co-PIs on the grant were well aware of this criticism and understood their origins. As the programme progressed, it became apparent from our students’ interactions with industry representatives that the private sector was searching for PhD-level employees who had greater breadth than those that they were generally encountering.

We recently polled some of our now advanced molecular biology graduate students about their perspectives on the depth of their training. They were all confident that they could match their peers in genetics and entomology in terms of depth. They did say that they had taken a couple fewer disciplinary courses than their peers in those departments, but they had learned the important subject matter on their own. Some felt that it would take them one extra year to complete their degrees because of the interdisciplinary work.

Each of the cohorts did a group project that resulted in a publication or website. Students in our third (last) cohort have published two peer reviewed interdisciplinary articles as a group’.

Source: Personal communication from Professor Fred Gould, North Carolina State University, December 2017

Box 2. edX course in industrial biotechnology

The edX course in industrial biotechnology is a joint initiative of TU Delft (the 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 [34]. 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.

tailored solutions for clients, ranging from operator through to senior management training. Further, it delivers training in a realistic environment with simulated 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.

8.6 Role for intermediate research organisations (IROs) and laboratories

IROs, typified by the Fraunhofer Society of Germany, can enable work in selected fields without the conflicting pressures of publishing and teaching explicit in academic research [37]. The concept seems enshrined in the UK Catapult model [38], 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).

8.7 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 [39]. Theories of business administration have their roots in commerce, which have in the past been focused on non-technological issues [40]. 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 knowledge gaps may be more appropriate.

A European 5 day mini-MBA has been offered in past that was tailored for mid-level chemical industry managers. 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.

SynbCITE developed a four-day MBA interactive course [41] that covered the main strategies required to establish, build and manage a biotechnology company built around engineering biology. It has focused on the early stages of setting up a company, getting funding and understanding the wider reaches of intellectual property.

8.8 Training technicians: establishing 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 and engineering biology should be part of their training, not all of it. Some foreseeable functions will be: routine maintenance of metabolically engineered strains; embedding engineering 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 [42]. Scale-up is a massive technical barrier in the bio-based industry, especially at the scale of transportation fuels [43], 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.
[44]. 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, community and further education colleges. This aligns well with thinking that envisages creation of biorefineries and bioeconomy clusters in rural and semi-rural environments as a means of rural regeneration.

One approach suggests an apprenticeship training route to keep day-release apprentices from companies close to the training centres. However, a ‘tyranny of small numbers’ has been identified in one geographical area to make it worthwhile for colleges to offer specialised industrial biotechnology courses [45]. This relates to industrial biotechnology and engineering biology being emerging sectors, and it will apply to any nation establishing bio-manufacturing.

The recently formed Industrial Biotechnology Innovation Centre in Scotland, jointly with three Scottish further education colleges, has established a Higher National Diploma in industrial biotechnology [46]. The qualification is intended to prepare students for employment as laboratory technicians, process operators and production scientists.

9 Limits of interdisciplinarity

We should also ask if there are limits to which interdisciplinarity can be taught for at least two reasons:

1. In the quest for breadth, depth may become too diluted. This could certainly be cause for concern in engineering degrees if professional bodies such as the Institution of Chemical Engineers [47] found too little depth to accredit engineers and courses fit-for-purpose.

2. The burden of learning required to become familiar, if not expert, in various different disciplines may be too great, which could be especially true within the time limitations of master programmes. The flexibility is greater within undergraduate degrees; nevertheless, careful attention would have to be given to curriculum design to prevent overload, with the attendant problem of student drop-out.

Regarding this latter point, it is worth remembering that the drop-out rates in STEM subjects (science, technology, engineering and mathematics) are already alarming: some 50% of American college students who major in STEM drop out [48].

10 Conclusions

Industrial biotechnology and engineering biology training requires a paradigm shift in how education is structured. Programmes are needed that encourage creativity and exploration, while harnessing the truly unique interdisciplinarity 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 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.

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