BIOTECHNOLOGY EDUCATION

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Contents

Summary

The scope and perspectives of education necessary for biotechnology are examined,

based on the perception that education has three separate but related levels: basic principles, skills, and values. Biotechnology is perceived as an interdisciplinary field with a high content of advanced scientific knowledge. This is documented with the list of Nobel prizewinners who, during the twentieth century, supported the advancement of biotechnology. There is a relation between innovative skills and economic development around the world. The requirement to integrate qualitative and quantitative knowledge in biotechnology is illustrated by the use of scale-up or allometric equations and their central role in extrapolating laboratory results to industrial applications. Amongst the many skills to be taught and learned, the most important is the skill to reason in order to apply basic principles to industrial use. Informatics and computation skills are needed more and more every day, but should not be used as a pretext to forget how to use imagination and logic in problem solving. Bioethical discussions now play a major role in the marketing of contemporary biotechnology. Major controversies on the use of genetically engineered agricultural products have limited the speed and extent at which those products are marketed around the world. Thus, teaching and learning of bioethics should be an important part of biotechnology education. Integration of basic principles, skills, and values make more sense if theory is confronted with practice. Hence, there is a strong need to incorporate on the job training as part of biotechnology education. Finally, international cooperation is a very promising and important way to overcome many gaps in biotechnology education around the world. In this area of education, much attention should be paid to South-South cooperation as a complementary part of traditional North-South cooperation projects.

1. Introduction

1.1. General Considerations

Education, in broad terms, should include basic principles, skills and values. Skills change from time to time and depend on market fluctuations, but basic principles and values have a more permanent status in our culture. Thus, it seems appropriate to divide the present discussion of education in biotechnology in terms of those levels of education.

Biotechnology is now touching on basic tenets on the reproduction of living systems, which almost demands the inclusion of an important discussion of values in the learning process of this field. For example, the controversy over the use of transgenic plants is a crystal clear example that basic principles and skills are not sufficient to assure the social acceptance of this kind of technology. To understand the nature of the controversies related to the use of biotechnology it is also necessary to understand the vested interests and values involved in the approval or disapproval of new versions of biotechnology.

On the other hand, ideology without basic scientific principles and advanced skills is not a good recipe for economic and social development. Global competition, the complexity of new technical problems, and the growing needs to use scientific expertise in modern biotechnology, impose the need for a good level of education as the springboard to successful international performance.

1.2. The Importance of Basic Knowledge in The Twenty-First Century

It is a common place observation, but important to remember, that the twenty-first century is becoming the century of information technology, as opposed to the nineteenth century which was marked by steam and steel technologies, and the twentieth century marked by chemical and electrical technologies. Technological development at the onset of the nineteenth century was based primarily on the initiative of private inventors. James Watt, Richard Arkwright, John Wilkinson and many others, produced independent but cooperative inventions that made possible the accelerated development of the textile industry in Northern England at the beginning of the nineteenth century. Such inventors had little academic training although they profited from influential personalities such as Joseph Black, who helped James Watt to understand the basic principles of heat balance when applied to steam engines. Professor Black, and John Anderson from Glasgow University, posed to Watt, who fabricated precision instruments, the need to have a steam engine working at a steady and high temperature. The purpose was to decrease the heat waste of the steam pump, invented by Thomas Newcomen, a smith from Dartmouth. Newcomen's engine was based on the alternation of condensation and expansion steam cycles. Professor Black had invented the notion of latent heat that helped to make the energy balance of Newcomen's pump. Watt, following Black's advice, went on to invent the steam piston engine on his own. Such an example of an inventor helped by a professor illustrates the fact that the steam and steel industrial revolution required mostly skilled engineers with a minimal scientific background to develop new contraptions in order to use coal energy to move textile

mills. During the electrical and chemical industrial revolution, developed mainly in Germany and USA at the beginning of the twentieth century, most inventions were put into practice by organized workshops financed by large enterprises. Isolated inventors were many but they required the back-up of well-established entrepreneurs who financed R&D institutions, such as the famous Edison laboratory in the US and the research groups in industrial chemistry at Bayer and Farber in Germany.

The present industrial revolution is based mainly on advanced scientific knowledge. For example, the advent of solid-state electronic devices was the outcome of basic research work on topics such as solid-state physics in the Massachusetts Institute of Technology and Bell laboratories during the Second World War. It was for this work that William Shockley was awarded the Nobel prize in physics in 1956, together with John Bardeen and Walter Houser Brattain. Their discovery of the transistor effect helped to start a new wave of innovations that led to the present boom in microelectronics and information technologies.

1.3. Definition and Scope of Biotechnology

Contemporary biotechnology can be defined as the optimal application of scientific knowledge of living systems to produce goods and services for the benefit of mankind. The distinction between traditional agriculture and biotechnology is now based on the high scientific content of modern applications.

An interesting way to illustrate the connection between science and biotechnology is to review the Noble prizes given in chemistry, physiology, and medicine during the twentieth century with the help of The Nobel Prize Archives (dates below correspond to the years in which Nobel prizes were awarded and not to dates of discoveries). Food fermentation can be documented through the millennia, but the understanding of the fermentation process of wine being due to the action of pure strains of yeast is credited to Pasteur (end of nineteenth century). Buchner (Nobel Prize in 1907) discovered that fermentation was the result of a mixture of enzymes inside the yeast cell. O.H. Warburg (1931) discovered the nature and mode of action of the respiratory enzyme. A. Fleming (1928) discovered penicillin, and E. Chain (1945) and H.W. Florey (1945) re-discovered the curative effect of this antibiotic in various infectious diseases, whereas S.A. Waksman (1952) discovered streptomycin, the first antibiotic effective against tuberculosis. Those discoveries were the dawn of large-scale fermentation processes with genetically improved strains of microorganisms.

J.B. Sumner, J.H. Northrop, and W.M. Stanley (1946) purified enzymes for the first time and F. Sanger (1958) found the way to unravel the chemical structure of proteins. The relationship between genes and enzymes was demonstrated by G.W. Beadle and E.L. Tatum (1958), and J. Lederberg (1958) made important advances concerning genetic recombination and the organization of the genetic material of bacteria. S. Ochoa (1959) together with A. Kornberg (1959) discovered the mechanisms in the biological synthesis of ribonucleic acid and deoxyribonucleic acid, whereas the three-dimensional models of DNA developed by F.H.C. Crick, (1962) J.D. (1962) Watson, and M.H. Wilkins (1962) allowed M.F. Perutz (1962) and J.C. Kendrew (1962) to describe the first tridimensional pictures of proteins. F. Jacob (1965), A. Lwoff (1965), and J.

Monod (1965) proposed the basic model of interaction between DNA and proteins, and R.W. Holley (1968), H.G. Khorana (1968), and M.W. Niremberg (1968) deciphered the genetic code linking DNA and protein structures. C.B. Anfinsen, S. Moore, and W.H. Stein (1972) described the basic relationship between the structure and function of enzymes. M. Delbrück, A.D. Hershey, and S.E. Luria earned the Nobel prize in 1969 for their discoveries concerning the replication mechanism and the genetic structure of viruses, and D. Baltimore, R. Dulbecco, and H.M. Temin in 1975 for their discoveries concerning the interaction between tumor viruses and the genetic material of the cell. After W. Arber, D. Nathans, H.O. Smith, and P. Berg carried out fundamental work on the transfer of genes between 1978 and 1980, W. Gilbert and F. Sanger (1980) developed the basic method of how to sequence nucleic acids. R.B. Merrifield (1984) developed a practical method of producing peptides by solid-state synthesis. Finally, K.B. Mullis developed a method, called polymerase chain reaction (PCR), to multiply DNA *in vitro*, and M. Smith developed a method to carry out site-directed mutagenesis in order to produce tailor made proteins (Noble laureates in 1993).

Such a long path of scientific discoveries makes the difference between empirical and scientific biotechnology. In the past, the practical use of living systems was based on the natural genetic variation of species. New breeds of organisms were developed by trial and error and there was no way to predict the outcome of genetic mutation. Now it is possible to make a rational design of a living process based on the chemical and physical properties of a few molecules, because gene structure can be deduced in terms of protein structure and the rules governing structure and function of living matter are better known every day.

Biotechnology is a very broad term (see *Biotechnology*). It is used to solve large-scale environmental problems, such as water treatment, soil bioremediation, and gas bioscrubbing (see *Environmental Biotechnology*). New pharmaceuticals are now based on the detailed knowledge of protein and DNA structures, and specific molecules can be produced in fermentation vats—for example, recombinant proteins, DNA fragments, and new antibiotics (see *Industrial Biotechnology*)**.** Rare food products can be produced for many uses by genetic manipulation of micro-organisms, for example, genes coding for cheese making enzymes, cloned from calves and expressed into active enzymes by yeast.(see *Fermentation and processing*) New corn and cottonseeds have been genetically engineered to produce biological pesticides that do not pollute the environment, and the number of biotechnological patents is increasing in many other fields of application. The market for biotechnology quadrupled every five to six years, mainly in the field of agriculture (see *Agricultural Biotechnology*), and new ideas are continuously being proposed, such as the desulfuration of diesel fuel using microbial cultures and leaching of metal ores using special lithotrophic bacteria (see *Biohydrometallurgy*).

1.4. The Practical Link between Basic Science and Biotechnology

The link between basic research and technological development is illustrated in the case of Genentech, which is now the largest R&D company in biotechnology. It was created as a result of research work done by Herbert Boyer at the University of California at San Francisco, and Stanley Cohen in Stanford University who found a practical way to transfer genes of a toad *Xenopus levis* to work inside the cells of a bacterium, *Escherichia coli*. In 1984, Cohen and Boyer filed for and, were accepted in 1988 as authors of, a US patent based on “Method and compositions ... provided for replication and expression of exogenous genes in microorganisms”. This patent was the technical justification for creating the Genentech Company that has now been awarded 578 patents on biotechnology by the US Patent Office and is partly owned by the pharmaceutical company Hoffman-LaRoche.

Thus, fast technological development at the San Francisco Bay Area and also in “Highway 69” near Boston were the cradles for the third industrial revolution. In this process, university spin-off biotechnology companies played a significant role, for example, Genentech, Cetus and Biogen, which are good examples of how academia and industries are now working closely together to develop this new wave of inventions using living systems in the production of goods and services. The strong connection between Nobel prizes and contemporary biotechnology gives credence to the idea that the twenty-first century experienced a new industrial revolution based on scientific knowledge.

1.5. Relations between Higher Education, Technological Innovation and Economic Development

Country	**Growth rate**
Mexico	5.9
Brazil	6.9

China	5.0
South Korea	40.4
Taiwan	28.2

Table 1. Comparison of growth rates (%) of the number of patents registered in the US Patent Office by nationals of selected countries (1980-1995).

A comprehensive analysis of the complex relations between scientific excellence, available venture capital, institutional support, and local demands for new products is far outside the scope of this article. But, work done by Hall and Castells shows how closely scientific knowledge and market development are linked in new information technologies. Nevertheless, industrial development around the world is marked by very large gaps between advanced and lagging economies. An interesting way to classify the regions around the world is to use the so-called innovation coefficient (IC: patents awarded to nationals in a given registry, per million nationals of a given country, a measure of the technological productivity of a country or groups of countries. Figure 1 shows how IC was distributed in 1994, according to data published by UNESCO, using information from the US Patent Office, which is not a complete catalogue of all patents around the world but is an indication of the intent of companies to compete in the largest national market. A level of IC greater than 40, seems to be the point for distinguishing between high and low competitive regions. Thus, our world population is divided into nearly 800 million people (16 percent) with access to advanced and new technologies, and 4200 million people (84 percent) almost deprived from the direct benefits of patent ownership. Unfortunately, there are large differences in the rate of change of the IC in different countries. For example, the IC index in South Korea and Taiwan has grown more than five times faster than in Mexico, Brazil, or China (see Table 1).

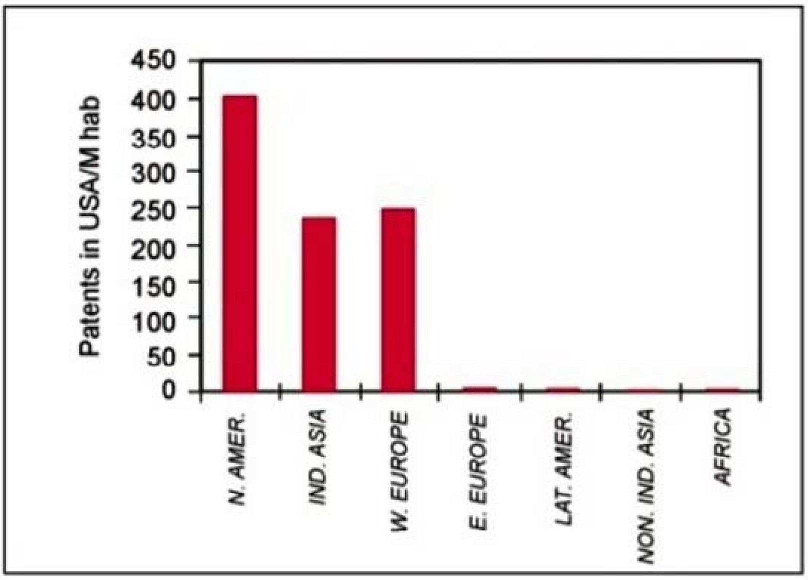

Figure 1. Distribution of the Innovation Coefficient (IC) in different regions of the world. [Data from Unesco 1994]. N.America: USA and Canada; Ind.Asia: Japan, South Korea, Taiwan, Singapore, Hong Kong, Australia, New Zealand; W.Europe: European

Union plus the other industrialized Western countries; E.Europe: former socialist European countries; Lat.America: includes Caribbean countries; Non.Ind.Asia: all other Asian nations excluding the former ones; Africa: the whole continent

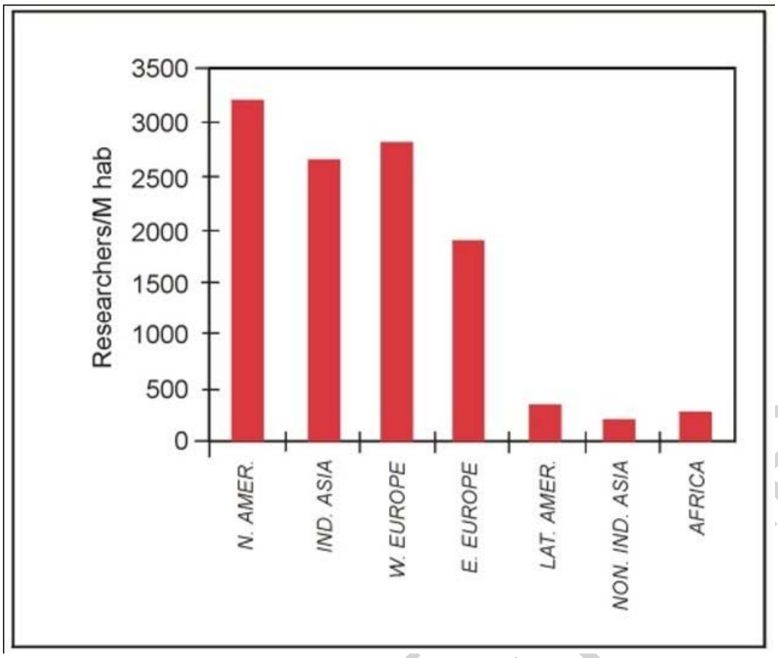

Figure 2. Availability of research workers in the various regions of the world defined in Figure 1. (Data from Unesco 1994.)

Figure 2 shows the relationship between technological productivity and the availability of scientific personnel around the world. It shows that most regions with a high level of IC (Figure 1) are the same as the regions with a high availability of scientific research workers (Figure 2). However, countries of Eastern Europe have a fair number of research workers (around 1800/million) available, but a negligible IC coefficient (less than 1 US patent/million). Figure 3 shows the differences in the relative level of investment on R&D among the regions of the world. Developed nations invest more than 1 percent of their Gross National Product (GNP) on R&D as compared to less than 0.5 percent in the least developed regions of the world. Again, with the exception of Eastern European countries, which invest more than 1 percent of their GNP in R&D. Figure 4 shows a positive quadratic correlation ($R_2 = 0.89$) between the level of IC and the average per capita income. Such correlation seems to confirm the need for a minimal threshold of IC (>40) to promote strong economic development. The fact that Eastern European countries have a fair level of investment on R&D and good availability of research workers, but a very low IC level and a low level of average income per capita, needs an explanation. It appears that investment on R&D and training of research workers is a necessary but not sufficient condition for economic development, because other local conditions, such as marketing and strategic planning, need to exist in order to make profits on R&D investment. Therefore, the IC index in the US Patent Office is a reflection of the effectiveness of commercial access to technology in a given country, which includes other factors besides higher education and R&D development. It is worth mentioning that many countries, such as Japan, have a much larger innovation coefficient when computed in their local patent registries than in the US Patent Office, but it is rather difficult to access the patent registries of many countries. However, studies published by the OCED (Organization of Countries for Economic Development) show similar trends for countries with high IC in the US Patent Office as compared to IC values in local registries.

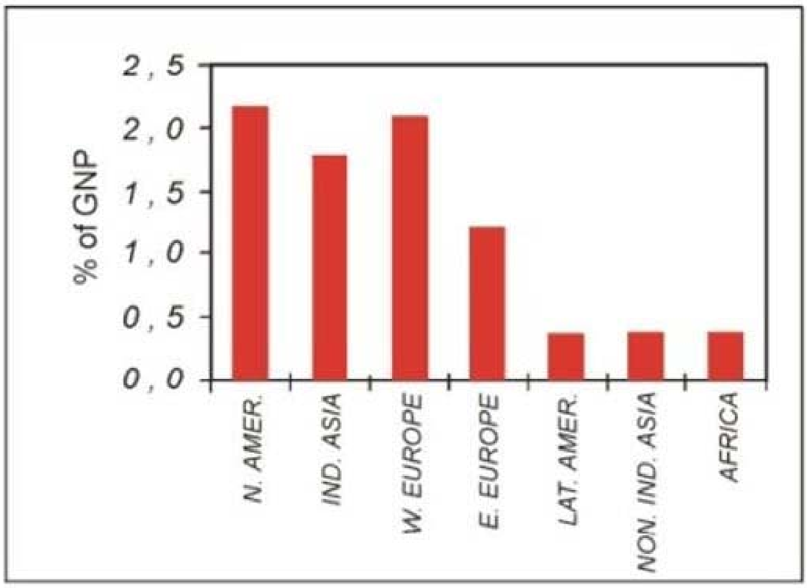

Figure 3. Percent of the average Gross National Product devoted to R&D in the regions defined in Figure 1. (Data from Unesco 1994.)

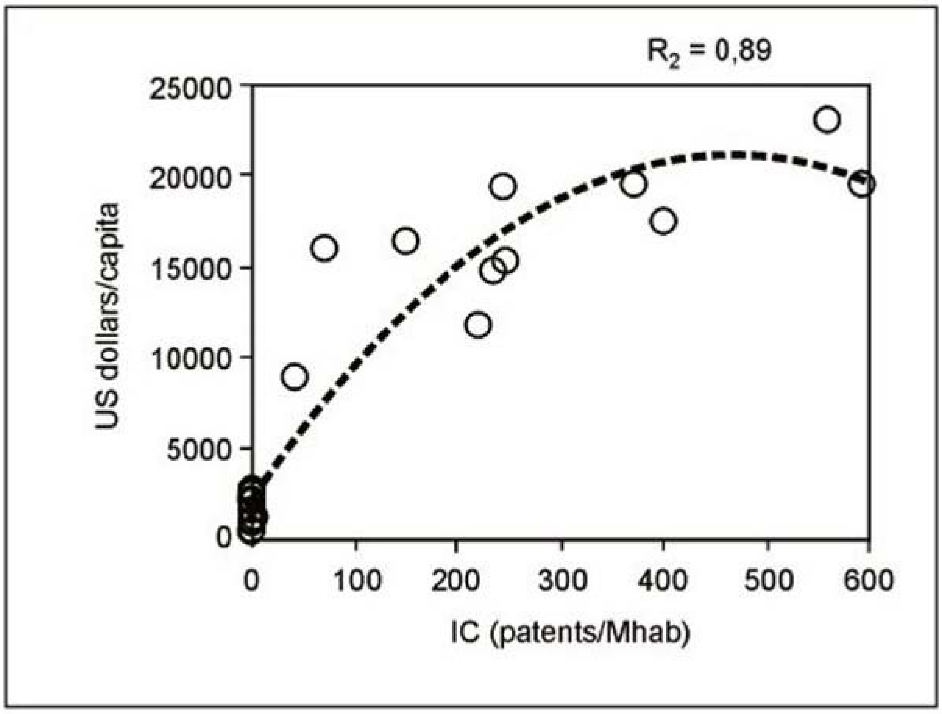

Figure 4. Parabolic correlation between the Innovation Coefficient (Figure 1) and average per capita income (GNP/populaiton) in the regions defined in Figure 1. (Data from Unesco 1994.)

In short, higher education in scientific disciplines seems to be part of the contemporary benchmarking of technology. Advanced nations invest more than 1 percent of the GNP on R&D, have more than 1,500 research workers per million people, and obtain more than 200 patents per million people assigned to their nationals in the US Patent Office, every year. Least advanced regions invest less than 0.5 percent of GNP on R&D, have less than 500 research workers per million people, and obtain less than 40 patents assigned to their nationals in the US Patent Office annually.

As mentioned above, education is not the only factor involved in economic development but, according to R. Solow, Nobel laureate in economics in 1994, it is important to consider the close integration between higher education, marketing strategy, and good manufacturing skills in order to achieve high levels of economic productivity. Therefore, as a consequence to this analysis, higher education in biotechnology should be considered as a major and necessary (but not sufficient) strategic factor in the benchmarking of biotechnology around the world.

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Biographical Sketch

Gustavo Viniegra-González. Born in Mexico City in 1940. Graduated at the Faculty of Medicine at the National Autonomous University of Mexico (UNAM) in 1965 and attained an M. Sc. in Biochemistry at the Centro de Investigación de Estudios Avanzados (CINVESTAV), Zacatenco campus in 1967. Obtained his Ph. D. degree in Biophysics from the University of California at San Francisco in 1971. He was postdoctoral fellow at the University of Pennsylvania, in the field of Enzyme Engineering, from 1971 until 1972. From 1972 to 1976 he was Investigador Titular at the Instituto de Investigaciones Biomédicas UNAM. He has been Professor of Biotechnology, since 1976, at the Universidad Autónoma Metropolitana (UAM) in Iztapalapa. He is now Distinguished Professor of UAM and National Investigator (level 3). His field of interest is solid-state fermentation with applications to environmental biotechnology.