The Green Revolution played a critical role in helping to overcome chronic food shortages in Latin America and Asia. The Green Revolution was largely a result of the creation of new institutional arrangements aimed at using existing technology to improve agricultural productivity. African countries are faced with enormous technological challenges. But they also have access to a much larger pool of scientific and technical knowledge than was available when the Green Revolution was launched in the 1950s. The aim of this chapter is to review major advances in science, technology, and engineering and identify their potential for use in African agriculture. This exploration will also include an examination of local innovations as well as indigenous knowledge. It will cover fields such as information and communications technology, genetics, ecology, and geographical sciences. It will emphasize the convergence of these and other fields and their implications for African agriculture.

Innovation and Latecomer Advantages

African countries can utilize the large aggregation of knowledge and know-how that has been amassed globally in their
efforts to improve their access to and use of the most cutting-edge technology. While Africa is currently lagging in the utilization and accumulation of technology, its countries have the ability not only to catch up to industrial leaders but also to attain their own level of research growth.

Advocates of scientific and technical research in developing countries have found champions in the innovation platforms of nanotechnology, biotechnology, information and communication technology (ICT), and geographic information systems (GIS). Through these four platform technologies, Africa has the opportunity to promote its agenda concurrent with advances made in the industrialized world. This opportunity is superior to the traditional catching-up model, which has led to slower development and kept African countries from reaching their full potential. These technologies are able to enhance technological advances and scientific research while expanding storage, collection, and transmission of global knowledge. This chapter explores the potential of ICT, GIS, nanotechnology, and biotechnology in Africa’s agricultural sector and provides examples of where these platform technologies have already created an impact.

Contemporary history informs us that the main explanation for the success of the industrialized countries lies in their ability to learn how to improve performance in a variety of fields—including institutional development, technological adaptation, trade, organization, and the use of natural resources. In other words, the key to success is putting a premium on learning and improving problem-solving skills.¹

Every generation receives a legacy of knowledge from its predecessors that it can harness for its own advantage. One of the most critical aspects of a learner’s strategy is using that legacy. Each new generation blends the new and the old and thereby charts its own development path within a broad technological trajectory, making debates about potential conflicts between innovation and tradition irrelevant.²
At least three key factors contributed to the rapid economic transformation of emerging economies. First, these countries invested heavily in basic infrastructure, including roads, schools, water, sanitation, irrigation, clinics, telecommunications, and energy. The investments served as a foundation for technological learning. Second, they nurtured the development of small and medium-sized enterprises (SMEs). Building these enterprises requires developing local operational, repair, and maintenance expertise, and a pool of local technicians. Third, government supported, funded, and nurtured higher education institutions as well as academies of engineering and technological sciences, professional engineering and technological associations, and industrial and trade associations.

The emphasis on knowledge should be guided by the view that economic transformation is a process of continuous improvement of productive activities, advanced through business enterprises. In other words, government policy should focus on continuous improvement aimed at enhancing performance, starting with critical fields such as agriculture for local consumption and extending to international trade.

This improvement indicates a society’s capacity to adapt to change through learning. It is through continuous improvement that nations transform their economies and achieve higher levels of performance. Using this framework, with government functioning as a facilitator for social learning, business enterprises will become the locus of learning, and knowledge will be the currency of change. Most African countries already have in place the key institutional components needed to make the transition to being a player in the knowledge economy. The emphasis should therefore be on realigning the existing structures and creating new ones where they do not exist.

The challenge is in building the international partnerships needed to align government policy with the long-term technological needs of Africa. The promotion of science and technology as a way to meet human welfare needs must, however,
take into account the additional need to protect Africa’s environment for present and future generations.

The concept of “sustainable development” has been advanced specifically to ensure the integration of social, economic, and environmental factors in development strategies and associated knowledge systems. Mapping out strategic options for Africa’s economic renewal will therefore need to be undertaken in the context of sustainable development strategies and action plans.

There is widespread awareness of rapid scientific advancement and the availability of scientific and technical knowledge worldwide. This growth feeds on previous advances and inner self-propelling momentum. In fact, the spread of scientific knowledge in society is eroding traditional boundaries between scientists and the general public. The exponential growth in knowledge is also making it possible to find low-cost, high-technology solutions to persistent problems.

Life sciences are not the only areas where research could contribute to development. Two additional areas warrant attention. The continent’s economic future crucially depends on the fate and state of its infrastructure, whose development will depend on the contributions of engineering, materials, and related sciences. It is notable that these fields are particularly underdeveloped in Africa and hence could benefit from specific missions that seek to use local material in activities such as road construction and maintenance. Other critical pieces involve expanding the energy base through alternative energy development programs. This sector is particularly important because of Africa’s past investments, its available human resources, and its potential to stimulate complementary industries that provide parts and services to the expansion of the sector. Exploiting these opportunities requires supporting policies.

Advances in science and technology will therefore make it possible for humanity to solve problems that have previously been in the realms of imagination. This is not a deterministic
view of society but an observation of the growth of global knowledge and the feasibility of new technical combinations that are elicited by social consciousness. This view would lead to the conclusion that Africa has the potential to access more scientific and technical knowledge than the more advanced countries had in their early stages of industrialization.

Recent evidence shows the role that investment in research plays in Africa’s agricultural productivity. For example, over the past three decades Africa’s agricultural productivity grew at a much higher rate (1.8%) than previously calculated, and technical progress, not efficiency change, was the primary driver of this crucial growth. This finding reconfirms the critical role of research and development (R&D) in agricultural productivity. The analysis also lends further support for the key role pro-trade reforms play in determining agricultural growth.

Within North Africa, which has experienced the highest of the continent’s average agricultural productivity growth (of 3.6% per year), Egypt stands out as a technology leader, as the gross majority of its agricultural growth has been attributable to technical investments and progress, not efficiency gains. A similar trend stressing the importance of technical progress and R&D has been seen in an additional 20 African countries that have experienced annual productivity growth rates over 2%.

This evidence shows that the adaptive nature of African agricultural R&D creates shorter gestation lags for the payout from R&D when compared to basic research. This makes the case for further investment even more important. On the whole, African agricultural productivity increased on net by 1.4% in the 1970s, 1.7% in the 1980s, and 2.1% in the 1990s. While growth in these decades can be attributed largely to major R&D investments made in the 1970s, declines in productivity growth in the 2000s are attributed to decreased R&D investments in the late 1980s and 1990s. With an average rate
of return of 33% for 1970–2004, sustained investment in adaptive R&D is demonstrated to be a crucial element of agricultural productivity and growth.

Evidence from other regions of the world tells the same story in regard to specific crops. For example, improvements in China’s rice production illustrate the significant role that technical innovation plays in agricultural productivity. Nearly 40% of the growth in rice production in 13 of China’s rice growing provinces over the 1978–84 period can be accounted for by technology adoption. Institutional reform could explain 35% of the growth. Nearly all the growth in the subsequent 1984–90 period came from technology adoption. These findings suggest that the impact of institutional reform, though significant, has previously been overstated. The introduction of new agricultural technologies went hand in hand with institutional reform.

“Chinese agriculture has grown rapidly during the past several decades, with most major crops experiencing increased yield, area harvested, and production. Between 1961 and 2004, maize, cotton, wheat, and oilseed production had an average growth rate of 4% per annum, while rice production growth was 2.8% per annum. However, the growth rates for wheat crops in terms of area harvested, yield, and production were less than 1% per annum between 1961 and 2004. A decomposition of the sources of wheat production growth indicates that growth between 1961 and 2004 was primarily driven by yield growth, with modest contribution from crop area. [In the case of North Korea, . . .] achieving self-sufficiency in food production has been one of the most important objectives of its economic strategy. Even so, the period between 1961 and 2004 saw minimal growth in area harvested for rice and soybeans and negative growth for maize and wheat.

Since the early 1960s, South Korea has transformed itself from a low-income agrarian economy into a middle-income
industrialized ‘miracle,’ and the agricultural sector in South Korea has not been immune to the tremendous structural change. . . . The decline in production in South Korea was continually driven by area contraction, whereas increased production was driven primarily by yield change in some cases and by area change in other instances . . . In an environment of poor natural resources and subsequent encroachment of the industrial and services sector on agriculture . . . Taiwan has experienced negative growth rates of rice, wheat, and oilseed area harvested from 1961 until 2004.”

In most cases, production growths were due to increased yields and production decreases were due to contractions in crop area.

**Generic or Platform Technologies**

**Information and Communications Technologies**

While information and communication technologies in industrialized countries are well developed and historically established, ICTs in developing countries have traditionally been “based on indigenous forms of storytelling, song and theater, the print media and radio.” Despite Africa’s current deficiency in more modern modes of communication and information sharing, the countries benefit greatly from the model of existing technologies and infrastructure.

In addition to the specific uses that will be explored in the rest of this section, ICTs have the extremely significant benefit of providing the means for developing countries to contribute to and benefit from the wealth of knowledge and research available in, for example, online databases and forums. The benefits of improved information and communication technologies range from enhancing the exchange of inter- and intra-continental collaborations to providing agricultural applications through the mapping of different layers of local landscapes.
Mobile Technology

Sub-Saharan Africa has 10 times as many mobile phones as landlines in operation, providing reception to over 60% of the population. Much of this growth in cell phone use—as much as 45% annually from 2002 through 2011—coincided with economic growth in the region. It is estimated that every 10% growth in mobile phones can raise up to 1.5% in GDP growth. There are five ways in which mobile phone access boosts microeconomic performance: reducing search costs and therefore improving overall market efficiency, improving productive efficiency of firms, creating new jobs in telecommunications-based industries, increasing social networking capacity, and allowing for mobile development projects to enter the market.13

Mobile phones cut out the opportunity costs, replacing several hours of travel with a two-minute phone call and also allow firms and producers to get up-to-date information on demand. They also redistribute the economic gains and losses per transaction between consumers and producers. This reduction in the costs of information gathering creates an ambiguous net welfare gain for consumers, producers, and firms. Similarly, mobile phones make it easier for social networks to absorb economic shocks. Family and kinship relationships have always played an important role in African society, and mobile phones strengthen this already available “social infrastructure,” allowing faster communication about natural disasters, epidemics, and social or political conflicts.

The use of more mobile phones creates a demand for additional employment. For instance, formal employment in the private transport and communications sector of Kenya rose by 110% between 2003 and 2011, as mobile phone use rose about 45% annually during that period. While there is a measurable growth in formal jobs, such as hotline operators who deliver information on agricultural techniques, there is also growth in
the informal sector, including the sale of phone credit and “pay-as-you-go” phones, repair and replacement of mobile phone hardware, and operation of phone rental services in rural areas. New employment opportunities also come through the mobile development industry.

Africa’s advantage over countries like the United States in avoiding unnecessary infrastructure costs is especially exemplified in the prevalence of mobile technologies, which have replaced outdated landline connectivity. Mobile phones have a proven record in contributing to development, as illustrated by the associated rise in the rate of mobile phone use, averaging 65% annually over the last five years.14 Because mobile phones are easy to use and can be shared, this mobility has revolutionized and facilitated processes like banking and disease surveillance.

The potential and current uses of mobile technology in the agricultural sector are substantial and varied. For instance, local farmers often lacked the means to access information regarding weather and market prices making their job more difficult and decreasing their productivity. With cellular phones comes cheap and convenient access to information such as the cost of agricultural inputs and the market prices for crops.

The desire for such information has led to the demand for useful and convenient mobile phone-based services and applications: “New services such as AppLab, run by the Grameen Foundation in partnership with Google and the provider MTN Uganda, are allowing farmers to get tailored, speedy answers to their questions. The initiative includes platforms such as Farmer’s Friend, a searchable database of agricultural information, Google SMS, a question and answer texting service and Google Trader, a SMS-based ‘marketplace’ application that helps buyers and sellers find each other.”15 Applications such as these coupled with the increased usage of cellular phones have reduced the inefficiencies and unnecessary expenses of travel and transportation.
Simple services like text messaging have likewise led to an expansion of access and availability of knowledge. This service has been enhanced by nonprofit Kiwanja.Net’s development of a software package allowing the use of text message services where there is no Internet, so long as one has a computer. Other advantages include the ability to set up automatic replies to messages using keywords (for example, in the case of a scheduled vaccination). Nongovernmental organization (NGO) managers, doctors, and researchers around the world have enthusiastically picked up this technology and used it to solve their communication challenges—from election monitoring, to communicating health and agricultural updates, to conducting surveys, to fund-raising—the list is endless.

From opening access to research institutes to facilitating business transactions, few technologies have the potential to revolutionize the African agricultural sector as much as the Internet. The demand for Internet service in Africa has been shown in the large increases in Internet usage (over 1,000% between 2000 and 2008) and through the fiber-optic cable installed in 2009 along the African east coast by Seacom. By 2011 four new undersea fiber optical cables were serving African western and eastern coasts. Just as with mobile phones, the Internet will have a transformative impact on the operations of businesses, governments, NGOs, farmers, and communities alike.

Until recently Africa was served by an undersea fiber-optic cable only on the west coast and in South Africa. The rest of the continent relied on satellite communication. The first undersea fiber-optic cable, installed by Seacom, reached the east African coast in July 2009. The US$600 million project will reduce business costs, create an e-commerce sector, and open up the region to foreign direct investment.

New industries that create content and software are likely to emerge. This will in turn stimulate demand for access devices. A decade ago it cost more than US$5,000 to install one km of standard fiber-optic cable. The price has dropped to less than
US$300. However, for Africa to take advantage of the infra-
structure, the cost of bandwidth must decline. Already, Internet
service providers are offering more bandwidth for the same
cost. By 2011 the four undersea cables operating in Africa had
resulted in a quadrupling of data transfer speeds and a 90% price reduction.

Access to broadband is challenging Africa’s youth to demon-
strate their creativity and the leaders to provide a vision of the role of infrastructure in economic transformation. The emergence of Safaricom’s M-PESA service—a revolutionary way to transmit money by mobile phones—is an indicator of great prospects for using new technologies for economic improvement. In fact, these technologies are creating radically new industries such as branchless banks that are revolution-
izing the service sector.

The diffusion of GIS is creating new opportunities for develop-
ment in general and Africa in particular, with regard to agri-
culture. An example of the potential GIS has for agriculture is the digitalization of more than 20 million land records under the Bhoomi Project in India’s State of Karnataka, which led to improved and more available information on land rights and land use innovation. But the implications of the Bhoomi Project did not just stop here. Because of the availability of such geospatial information, bankers became more inclined to provide crop loans and land disputes began declining, allowing farmers to invest in their land without fear. The success of this project has inspired the government of India to establish the National Land Records Modernisation Programme to do the same for the entire country. Not only does this show the applicability and usefulness of information technologies in agriculture, but it also provides an option to be considered by African countries.

Unlike biotechnology and nanotechnology, ICT and GIS do not have as much risk of being overregulated or reviled for being a great unknown. However, regulation of ICT and GIS will be necessary—and keeping clients and users secure will be
a challenge as more and more of Africa becomes connected to the international network. Balancing privacy with the benefits of sharing knowledge will probably be one of the largest challenges for these sectors, especially between countries and companies.

When introducing new technologies in the field, policy makers should consider ones that are low cost and easily accessible to the farmers who will use them. They should ideally capitalize on techniques that farmers already practice and involve support for scaling up and out, rather than pushing for expensive and unfamiliar practices.

New technologies should also allow farmers to be flexible according to their own capacities, situations, and needs. They should require small initial investments and let farmers experiment with the techniques to decide their relative success. If farmers can achieve success with a small investment early on, they are likely to devote more resources to the technique later as they become committed to the practice. An example of this type of technological investment is the planting pits that increased crop production and fostered more productive soil for future years of planting.

Mobile technologies are poised to influence a wide range of sectors. For example, by 2011 the One Laptop per Child (OLPC) Foundation had provided over two million rugged, low-cost, low-power XO laptops to school children around the world. The laptops come with software and content designed to foster collaborative and interactive child-centered learning. Advances in complementary technologies and increased availability of digital books will make education more mobile. Learning will no longer be restricted to classrooms. Emerging trends in mobile technology will also transform health care. Portable ultrasound devices produced by firms such as General Electric, SonoSite, and Masimo will help to reduce the cost of health care. Technological convergence will also simplify the use of new technologies and make them more widely accessible.
Biotechnology

Biotechnology—technology applied to biological systems—has the promise of leading to increased food security and sustainable forestry practices, as well as improving health in developing countries by enhancing food nutrition. In agriculture, biotechnology has enabled the genetic alteration of crops, improved soil productivity, and enhanced natural weed and pest control. Unfortunately, such potential has largely remained untapped by African countries.

In addition to increased crop productivity, biotechnology has the potential to create more nutritious crops. About 250 million children suffer from vitamin A deficiency, which weakens their immune systems and is the biggest contributor to blindness among children. Other vitamins, minerals, and amino acids are necessary to maintain healthy bodies, and a deficiency will lead to infections, complications during pregnancy and childbirth, and impaired child development. Biotechnology has the potential to improve the nutritional value of crops, leading both to lower health care costs and higher economic performance (due to improved worker health).

Tissue culture has not only helped produce new rice varieties in Africa but has also helped East Africa produce pest- and disease-free bananas at a high rate. The method’s ability to rapidly clone plants with desirable qualities that are disease-free is an exciting prospect for current and future research on improved plant nutrition and quantities. Tissue culture has also proved to be useful in developing vaccines for livestock diseases, especially the bovine disease rinderpest. Other uses in drug development are currently being explored.

Tissue culture of bananas has had a great impact on the economy of East African countries since the mid-1990s. Because of its susceptibility to disease, banana has always been a double-edged sword for the African economies like that of
Uganda, which consumes a per capita average of one kilogram per day. For example, when the Black Sigatoka fungus arrived in East Africa in the 1970s, banana productivity decreased as much as 40%. Tissue culture experimentation allowed for quick generation of healthy plants and was met with great success. Since 1995, Kenyan banana production has more than doubled, from 400,000 to over one million tons in 2004, with average yield increasing from 10 tons per hectare to 30–50 tons.

Marker-assisted selection helps identify plant genome sections linked to genes that affect desirable traits, which allows for the quicker formation of new varieties. This technique has been used not only to introduce high-quality protein genes in maize but also to breed drought-tolerant plant varieties. An example of a different application of this method has been the development of maize resistant to Maize streak virus. While the disease has created a loss of 5.5 million tons per year in maize production, genetic resistance is known and has the potential of greatly raising production. The uptake of genetically modified (GM) crops is the fastest adoption rate of any crop technology, increasing from 1.7 million hectares in 1996 to 160 million hectares in 2011, and a 94-fold increase over the period.21

Recent increases among early adopting countries have come mainly from the use of “stacked traits” (instead of single traits in one variety or hybrid). In 2011, for example, 88% of the 37.4 million hectares of maize grown in the United States was genetically modified, and three-quarters of this involved hybrids with double or triple stacked traits. Nearly 90% of the cotton growth in the United States, Australia, and South Africa is GM and, of that, 75% has double-stacked traits.

In 2011, there were 16.7 million farmers growing GM crops in 29 countries around the world, of whom over 90% were small and resource-poor farmers from developing countries. Most of the benefits to such farmers have come from cotton. For
example, over the 2002–10 period, *Bacillus thuringiensis* (Bt) cotton added US$9.4 billion worth of value to Indian farmers, cut insecticide use by half, helped to double yield and turned the country from a cotton importer into a major exporter.22

Africa is steadily joining the biotechnology revolution. South Africa’s GM crop production stood at 2.3 million hectares in 2011. Burkina Faso grew 300,000 hectares of Bt cotton the same year, up from 260,000 in 2010. It had the fastest adoption rate of a GM crop in the world in 2009. In 2011, Egypt planted nearly 2,800 hectares of Bt maize, an increase of 40% over 2010.23

African countries, by virtue of being latecomers, have had the advantage of using second-generation GM seed. Monsanto’s Genuity™ Bollgard II® (second generation) cotton contains two genes that work against leaf-eating species such as armyworms, budworms, bollworms, and loopers. They also protect against cotton leaf perforators and saltmarsh caterpillars. Akin to the case of mobile phones, African farmers can take advantage of technological leapfrogging to reap high returns from transgenic crops while reducing the use of chemicals. In 2010 Kenya and Tanzania announced plans to start growing GM cotton in view of the anticipated benefits of second-generation GM cotton. The door is now open for revolutionary adoption of biotechnology that will extend to other crops as technological familiarity and economic benefits spread.

There is also a rise in the adoption of GM crops in Europe. In 2011, eight European countries (Spain, Czech Republic, Portugal, Romania, Poland, Slovakia, Germany, and Sweden) planted commercial Bt maize. Trends in Europe suggest that future decisions on GM crops will be driven by local needs as more traits become available. For example, crops that tolerate various stresses such as drought are likely to attract interest among farmers in Africa. The Water Efficient Maize for Africa project, coordinated by the African Agricultural Technology Foundation in collaboration with the International Centre for the
Improvement of Maize and Wheat (CIMMYT) and Monsanto and support from the Howard Buffett Foundation and the Bill and Melinda Gates Foundation, is an example of such an initiative that also brings together private and public actors.\textsuperscript{24}

This case also represents new efforts by leading global research firms to address the concerns of resource-poor farmers, a subtheme in the larger concern over the contributions of low-income consumers.\textsuperscript{25} Other traits that improve the efficiency of nitrogen uptake by crops will also be of great interest to resource-poor farmers. Other areas that will attract interest in developing new GM crops will include the recruitment of more tree crops into agriculture and the need to turn some of the current grains into perennials.\textsuperscript{26}

Trends in regulatory approvals are a good indicator of the future of GM crops. By 2011, some 29 countries had planted commercial GM crops and another 31 had approved GM crop imports for food and feed use and for release into the environment. A total of 1,045 approvals have been granted for 196 events (unique DNA recombinations in one plant cell used to produce entire GM plants) for 25 crops. GM crops are accepted for import in 60 countries (including Japan, the United States, Canada, South Korea, Mexico, Australia, the Philippines, the European Union (EU), New Zealand, and China). The majority of the events approved are in maize (65) followed by cotton (39), canola (15), potato (14), and soybean (14).\textsuperscript{27}

Because of pest attacks, cotton was, until the early 1990s, the target of 25\% of worldwide insecticide use.\textsuperscript{28} Recombinant DNA engineering of a bacterial gene that codes for a toxin lethal to bollworms resulted in pest-resistant cotton, increasing profit and yield while reducing pesticide and management costs.\textsuperscript{29} Countries like China took an early lead in adopting the technology and have continued to benefit from reduced use of pesticides.\textsuperscript{30}

While GM crops have the potential to greatly increase crop and livestock productivity and nutrition, a popular backlash
against GM foods has created a stringent political atmosphere under which tight regulations are being developed. Much of the inspiration for restrictive regulation comes from the Cartagena Protocol on Biosafety under the United Nations Convention on Biological Diversity. The central doctrine of the Cartagena Protocol is the “precautionary principle” that empowers governments to restrict the release of products into the environment or their consumption even if there is no scientific evidence that they are harmful.

These approaches differ from food safety practices adopted by the World Trade Organization (WTO) that allow government to restrict products when there is sufficient scientific evidence of harm. Public perceptions are enough to trigger a ban on such products. Those seeking stringent regulation have cited uncertainties such as horizontal transfer of genes from GM crops to their wild relatives. Others have expressed concern that the development of resistance to herbicides in GM crops results in “super-weeds” that cannot be exterminated using known methods. Some have raised fears about the safety of GM foods to human health. Other concerns include the fear that farmers would be dependent on foreign firms for the supply of seed.

The cost of implementing these regulations could be beyond the reach of most African countries. Such regulations have extended to African countries, and this tends to conflict with the great need for increased food production. As rich countries withdraw funding for their own investments in agriculture, international assistance earmarked for agricultural science has diminished.

In June 1999, five European Union members (Denmark, Greece, France, Italy, and Luxembourg) formally declared their intent to suspend authorization of GM products until rules for labeling and traceability were in place. This decision followed a series of food-related incidents such as “mad cow disease” in the UK and dioxin contamination in Belgium. These events
undermined confidence in regulatory systems in Europe and raised concerns in other countries. Previous food safety incidents tended to shape public perceptions over new scares. In essence, public responses reactions to the GM foods were shaped by psychological factors. Much of this was happening in the early phases of economic globalization when risks and benefits were uncertain and open to question, including the very moral foundations of economic systems.

Much of this debate occurred at a time of increased awareness about environmental issues and there had been considerable investment in public environmental advocacy to prepare for the 1992 United Nations Conference on Environment and Development in Rio de Janeiro. These groups teamed up with other groups working on issues such as consumer protection, corporate dominance, conservation of traditional farming practices, illegal dumping of hazardous waste, and promotion of organic farming to oppose the introduction of GM crops. The confluence of forces made the opposition to GM crops a global political challenge, which made it easier to try to seek solutions through multilateral diplomatic circles.

The moratorium was followed by two important diplomatic developments. First, the EU used its influence to persuade its trading partners to adopt similar regulatory procedures that embodied the precautionary principle. Second, the United States, Canada, and Argentina took the matter to the WTO for settlement in 2003. Under the circumstances, African countries opted for a more restrictive approach partly because they had stronger trade relations with the EU and were therefore subject to diplomatic pressure. Their links with the United States were largely through food aid programs.

In 2006, the WTO issued its final report on the dispute; the findings were largely on procedural issues and did not resolve the root cause of the debate such as the role of the “precautionary principle” in WTO law and whether GM foods were
substantially equivalent to their traditional counterparts. By then a strong anti-biotechnology culture had entrenched itself in most African countries. For example, even after developing a GM potato resistant to insect damage, Egypt refused to approve it for commercial use. This resistance grew to the point that Africa ceased to accept unmilled GM maize from the United States as food aid. A severe drought in 2001–02 left 15 million Africans with severe food shortages; countries like Zimbabwe and Zambia turned down shipments of GM maize, fearing that the kernels would be planted instead of eaten. Unlike the situation in rich countries, GM foods in developing countries have the potential to revolutionize the lots of suppliers and consumers. In order to take full advantage of the many potentials of biotechnology in agriculture, Africa should consider whether aversion to and overregulation of GM production are warranted.

In Nigeria, the findings of a study on biotechnology awareness demonstrate that while respondents have some awareness of biotechnology techniques, this is not the case for biotechnology products. Most of the respondents are favorably disposed to the introduction of GM crops and would eat GM foods if they are proven to be significantly more nutritious than non-GM foods. The risk perception of the respondents suggests that although more people are in favor of the introduction of GM crops, they, however, do not consider the current state of Nigeria’s institutional preparedness satisfactory for the approval and release of genetically modified organisms (GMOs).

However, it is important to consider that African farmers will not grow successful crops if prices are low or dropping. Additionally, complications with regulation and approval of GM crops make obtaining commercial licenses to grow certain crops difficult. Also, neighboring countries must often approve similar legislation to cover liabilities that might arise from cross-pollination by wind-blown pollen, for example. Biosafety
regulations often stall developments in the research of GM crops and could have negative impacts on regional trade.\textsuperscript{45}

For these reasons, approval and use of potentially beneficial crops are often difficult. However, despite potential setbacks, biotechnology has the potential to provide both great profits and the means to provide more food to those who need it in Africa. Leaders in the food industry in parts of Africa prefer to consider the matter on a case-by-case basis rather adopt a generic approach to biosafety.\textsuperscript{46} In fact, the tendency in regulation of biotechnology appears to follow more divergence paths reflecting unique national and regional attributes.\textsuperscript{47} This is partly because regulatory practices and trends in biotechnology development tend to co-evolve as countries seek a balance between the need to protect the environment and human safety and fostering technological advancement.\textsuperscript{48}

Advancements in science have allowed scientists to insert characteristics of other plants into food crops. Since the introduction of GM crops in 1996, over 80\%-90\% of soybean, corn, and cotton grown in the United States today comes from GM crops. Despite their widespread use, there are limited data on their environmental, economic, and social impact.\textsuperscript{49}

Herbicide-resistance GM crops have fewer adverse effects on the environment than natural crops, but often at the cost of farming efficiency. The growth of most crops requires the use of toxic chemical herbicides, but GM crops utilize an organic compound called glyphosphate to combat weeds. While less dangerous toxins are entering the environment, weeds are developing a resistance to glyphosphate in soybean, corn, and cotton crops, reducing farming efficiency and raising prices on these goods.

GM corn and cotton have helped reduce the amount of insecticides entering the environment. Insecticides are harmful to most insects, regardless of their impact, positive or negative, on crops. Genetically engineered corn and cotton produce \textit{Bacillus thuringiensis} (Bt) toxins, which kill the larvae of beetles,
Advances in Science, Technology, and Engineering  43

moths, and flies. New genetic hybrids are introduced frequently to reduce the threat of a Bt resistant pest. Since 1996, insecticide use has decreased while Bt corn use has grown considerably. While the environmental benefits are clear, GM crops pose a threat to farmers who rely on nonengineered crops. Inter-breeding between crops is difficult to stop, so regulatory agencies must set clear standards on how much GM material is allowed to be present in organic crops.

The rapid adoption of GM crops seems to indicate that they offer great economic benefits for farmers. In general, farmers experience lower production costs and higher yields because weed control is cheaper and fewer losses are sustained from pests. GM crops are safer to handle than traditional chemical pesticides and herbicides, increasing worker safety and limiting the amount of time workers spend in the field. While the supply-side benefits for farmers are clear, it is not completely understood how genetic modification affects the market value for these crops. Holding technological achievement constant, any gains tend to dissipate over time.

The United States has benefited by being among the first adopters of GM crops. In a similar vein, it is not clear what economic effects planting GM crops will have on farmers who do not adopt the technology. Livestock farmers are one of the largest customers of corn and soybean for feed and should receive the largest benefits of the downward pressure on prices from transgenic crops, yet no study has been conducted on such effects. Similarly, it is possible that the growing use of GM crops leaves many pests resistant to chemicals to ravage the fields of nonadopters, forcing them to use higher concentrations of dangerous chemicals or more expensive forms of control. In the future, new public policy will be needed to develop cost-effective methods of controlling the growing weed resistance to glyphosate.

It is important to recognize that developing countries face a separate set of risks from those of industrialized countries.
For example, new medicines could have different kinds and levels of effectiveness when exposed simultaneously to other diseases and treatments. Similarly, “new technologies may require training or monitoring capacity which may not be locally available, and this could increase risks associated with the technology’s use.”\textsuperscript{50} This has been demonstrated where a lack of training in pesticide use has led to food contamination, poisoning, and pesticide resistance. In addition, the lack of consistent regulation, product registration, and effective evaluation are important factors that developing Africa will need to consider as it continues its exploration of these platform technologies. Probably the most significant research and educational opportunities for African countries in biotechnology lie in the potential to join the genomics revolution as the costs of sequencing genomes drop. When James Watson, co-discover of the DNA double-helix, had his genome sequenced in 2008 by 454 Life Sciences, the price tag was US$1.5 million. A year later a California-based firm, Applied Biosystems, revealed that it has sequenced the genome of a Nigerian man for under US$60,000. In 2010 another California-based firm, Illumina, announced that it had reduced the cost to about US$20,000.

Dozens of genomes of agricultural, medical, and environmental importance to Africa have already been sequenced. These include human, rice, corn, mosquito, chicken, cattle, and dozens of plant, animal, and human pathogens. The challenge facing Africa is building capacity in bioinformatics to understanding the location and functions of genes. It is through the annotation of genomes that scientists can understand the role of genes and their potential contributions to agriculture, medicine, environmental management, and other fields. Bioinformatics could do for Africa what computer software did for India. The field would also give African science a new purpose and help to integrate the region into the global knowledge ecology. This opportunity offers Africa another opportunity for technological leapfrogging.
Nanotechnology

Of the four platform technologies discussed in this chapter, nanotechnologies are the least explored and most uncertain. Nanotechnology involves the manipulation of materials and devices on a scale measured by the billionths of a meter. The results of research in nanotechnology have produced substances of both unique properties and the ability to be targeted and controlled at a level unseen previously. Thus far, applications to agriculture have largely been theoretical, but practical projects have already been explored by both the private and public sectors in developed, emerging, and developing countries. 

For example, research has been done on chemicals that could target one diseased plant in a whole crop. Nanotechnology has the potential to revolutionize agriculture with new tools such as the molecular treatment of diseases, rapid disease detection, and enhancement of the ability of plants to absorb nutrients. Smart sensors and new delivery systems will help to combat viruses and other crop pathogens. Increased pesticide and herbicide effectiveness as well as the creation of filters for pollution create more environmentally friendly agriculture process. While countries like the United States and China have been at the forefront of nanoscience research expenditure and publications, emerging countries have engaged in research on many of the applications, from water purification to disease diagnosis.

Water purification through nanomembranes, nanosensors, and magnetic nanoparticles have great, though currently cost prohibitive, potential in development, particularly in countries like Rwanda, where contaminated water is the leading cause of death. However, the low energy cost and high specificity of filtration has lead to a push for research in water filtration and purification systems like the Seldon WaterStick and WaterBox. Developed by U.S.-based Seldon Laboratories, these products require low energy usage to filter various pathogens and
chemical contaminants and are already in use by aid workers in Rwanda and Uganda.\textsuperscript{52}

One of the most promising applications of nanotechnology is low-cost, energy-efficient water purification. Nearly 300 million people in Africa lack access to clean water. Water purification technologies using reverse osmosis are not available in much of Africa, partly because of high energy costs. Through the use of a “smart plastic” membrane, the U.S.-based Dais Analytic Corporation has developed a water purification system that could significantly increase access to clean water and help to realize the recent proclamation by the United Nations that water and sanitation are fundamental human rights.

The capital costs of the NanoClear technology are about half the cost of using reverse osmosis water purification system. The new system uses about 30% less energy and does not involve toxic elements. The system is modular and can be readily scaled up on demand. A first-generation pilot plant opened in Tampa, Florida, in 2010 to be followed later in the year by the deployment of the first fully operational NanoClear water treatment facility in northern China. The example of NanoClear illustrates how nanotechnology can help provide clean water, reduces energy usage, and charts an affordable course toward achieving sustainable development goals.\textsuperscript{53}

The potential for technologies as convenient as these would revolutionize the lifestyles of farmers and agricultural workers in Africa. Both humans and livestock would benefit from disease-free, contaminant-free water for consumption and agricultural use.

The cost-prohibitive and time-intensive process of diagnosing disease promises to be improved by nanotechnological disease diagnostics. While many researchers have focused on human disease diagnosis, developed and developing countries alike have placed an emphasis on livestock and plant pathogen identification in the interest of promoting the food
Advances in Science, Technology, and Engineering

and agricultural industry. Nanoscience has offered the potential of convenient and inexpensive diagnosis of diseases that would otherwise take time and travel. In addition, the convenient nanochips would be able to quickly and specifically identify pathogens with minimal false diagnoses. An example of this efficiency is found in the EU funded Optolab Card project, whose kits allows a reduction in diagnosis time from 6–48 hours to just 15 minutes.

Technology Monitoring, Prospecting, and Research

Much of the debate on the place of Africa in the global knowledge economy has tended to focus on identifying barriers to accessing new technologies. The basic premise has been that industrialized countries continue to limit the ability of developing countries to acquire new technologies by introducing restrictive intellectual property rights. These views were formulated at a time when technology transfer channels were tightly controlled by technology suppliers, and developing countries had limited opportunities to identify the full range of options available to them. In addition, they had limited capacity to monitor trends in emerging technologies. But more critically, the focus on new technologies as opposed to useful knowledge hindered the ability of developing countries to create institutions that focus on harnessing existing knowledge and putting it to economic use.

In fact, the Green Revolution and the creation of a network of research institutes under the Consultative Group on International Agricultural Research (CGIAR) represented an important example of technology prospecting. Most of the traits used in the early breeding programs for rice and wheat were available but needed to be adapted to local conditions. This led to the creation of pioneering institutions such as CIMMYT in Mexico and the International Rice Research Institute (IRRI) in the Philippines.54
Other countries have used different approaches to monitor, identify, and harness existing technologies, with a focus on putting them to commercial use. One such example is the Fundación Chile, established in 1974 by the country’s Minister for Economic Cooperation, engineer Raúl Sáez. The Fundación Chile was set up as joint effort between the government and the International Telephone and Telegraph Corporation to promote research and technology acquisition. The focus of the institution was to identify existing technologies and match them to emerging business opportunities. It addressed a larger goal of helping to diversity the Chilean economy and created new enterprises based on imported technologies.\(^{35}\)

But unlike their predecessors who had to manage technological scarcity, Africa’s challenge is managing an abundance of scientific and technological knowledge. The rise of the open access movement and the growing connectivity provided by broadband Internet now allows Africa to dramatically lower the cost of technology searches. But such opportunities require different technology acquisition strategies. First, they require the capacity to assess the available knowledge before it becomes obsolete. Second, such assessments have to take into account the growing convergence of science and technology.\(^{56}\) There is also an increasing convergence between different disciplines.

Moreover, technology assessments must now take into account social impacts, a process that demands greater use of the diverse disciplines.\(^{57}\) Given the high rate of uncertainty associated with the broader impact of technology on environment, it has become necessary to incorporate democratic practices such as public participation in technology assessments.\(^{58}\) Such practices allow the public to make necessary input into the design of projects. In addition, they help to ensure that the risks and benefits of new technologies are widely shared.

Reliance on imported technology is only part of the strategy. African countries are just starting to explore ways to increase support for domestic research. This theme should be at the
center of Africa’s international cooperation efforts. These measures are an essential aspect of building up local capacity to utilize imported technology. This insight is important because the capacity to harness imported technology depends very much on the existence of prior competence in certain fields. Such competence may lie in national research institutes, universities, or enterprises. The pace of technology absorption is likely to remain low in countries that are not making deliberate efforts to build up local research capacity, especially in the engineering sciences. One way to address this challenge is to start establishing regional research funds that focus on specific technology missions.

Conclusion

The opportunities presented by technological abundance and diversity as well as greater international connectivity will require Africa to think differently about technology acquisition. It is evident that harnessing existing technologies requires a more detailed understanding of the convergence between science and technology as well the various disciplines. In addition, it demands closer cooperation between the government, academia, the private sector, and civil society in an interactive process. Such cooperation will need to take into account the opportunities provided by the emergence of Regional Economic Communities as building blocks for Africa’s economic integration. All the RECs seek to promote various aspects of science, technology and innovation in general and agriculture in particular. In effect, it requires that policy makers as well as practitioners think of economies as innovation systems that evolve over time and adapt to change. The next chapter will elaborate the idea of innovation systems and their implications for agricultural development and regional integration in Africa.