EMERGING TECHNOLOGICAL INNOVATION TRIAD FOR SMART AGRICULTURE IN THE 21ST CENTURITY. PART I. PROSPECTS AND IMPACTS OF NANOTECHNOLOGY IN AGRICULTURE

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ABSTRACT

Successful transformation of agriculture into a modern industry and the remarkable increases in factor productivity have contributed to improvement in human wellbeing. From an engineering perspective, agricultural mechanisation (as symbolised by the farm tractor) represents both a technology-push and technology-pull factor in the successful transformation of subsistence agriculture into market-oriented agribusiness. The availability of huge power units and related electromechanical systems for land preparation, cultivation, crop and livestock protection, harvesting and postharvest handling enabled humans to expand cultivated areas, convert otherwise marginal lands into productive units, and free up surplus farm labor to engage in non-farm service sectors that are equally rewarding. Particularly in developed economies, the percentage of population directly engaged in agriculture continues to diminish while outputs per farm labor continues to rise. Despite the tremendous advances made in increasing agricultural productivity through the application of modern technology, certain socio-political and economic factors contribute to declining terms of trade affecting agriculture in comparison to other blue-collar industries. The number of tertiary students choosing to study agriculture and related disciplines continues to decline.

In a recent article, we identified a technology triad (biotechnology, information and communication technology/ICT, and nanotechnology) which are poised to revolutionise agriculture in the 21st century (Opara, 2004). In the present article, we begin with an overview of the impacts of technological innovation on global agriculture and the socio-economic and technological challenges facing the industry. In the second section, we examine the meaning of nanotechnology and the potentials of nanoelectromechanisation in modern agriculture. We conclude by espousing some of the social, policy and ethical dilemmas facing the miniaturisation of eletromechanisation of agriculture (nanoagriculture). In future articles in this series, we will examine the remaining technologies in the triad (biotechnology and ICT) and their potenital impacts on future practice of agricultural and biosystems engineering.

***Keywords*:** nanotechnology, nanoagriculture, agricultural engineering, impacts

INTRODUCTION

Technological innovations have played significant roles in transforming agriculture and other land-based human endeavors into modern industries that produce a wide range of products and services. From our primordial beginings as food gatherers and hunters, the use of improved technology for crop, livestock and fisheries management have enabled humans to exploit natural resources to wield enhanced control over food, feed and fibre supply. The limitations and drudgery of human muscle as power source for agriculture were later overcome by the domestication of animals (such as oxen, buffalo and horses), which provided more efficient and reliable power sources for pulling agricultural implements and equipment for cultivation, irrigation, harvesting, transportation and agro-processing. Nevertheless, it was not until the advent of engine-powered mechanical technology (notably tractors and combines) that humans reached a momentous turning point in the application of engineering and technological innovations in agriculture and rural development.

Thereafter, it was evident that the availability and reliability of abundant and efficient farm power was essential to bring more land into production and increase overall agricultural efficiency. The availability of more efficient power sources spurred the design and development of new agricultural tools and machines, and also freed surplus labour to engage in off-farm economic activities in other industries. Agriculture was just no longer the practice of growing crops and animals in smallholdings for subsistence; it had evolved into an industry made up of more medium- and large-scale farmers who are in the business of producing food and raw materials to meet market demand.

Historically, science, engineering and technology (SET) have had both positive and negative consequences on humankind and the environment. In agriculture and other industries, the goals of SET are often value-laden; thus reflecting the economic and socio-cultural agenda of society spatially over space and time. The impacts of technological innovations have transformed the way we practice agriculture. Advances in agricultural SET have helped to avoid the human catastrophe predicted during the Malthusian era. It is arguable that problems facing over 800 million people without adequate food is much more a political and economic problem that technological. Yet the proportion of humankind affected by food insecurity and malnutrition continues to rise in many regions of the developing world and has been projected to continue in the foreseeable future.

Amidst the gloom and doom of lingering food insecurity and related poverty facing the rural agricultural population in developing countries, the future of agriculture on a global scale remains a subject of intense debate and scrutiny in terms of its declining terms of trade in comparison with other industries as well as its negative impacts on the environment. Obviously, modern innovative technologies are essential in tackling these problems facing agriculture and its relationship with society. Past technologies that are now part of our socio-economic fabric have had tremendous impacts on agriculture. The internal combustion engine of the industrial revolution era led to the development of the farm tractor which has become a lasting symbol of agricultural mechanisation. The "Green Revolution" of the 1960-70s resulted in considerable increases in yield in many parts of Asia and other parts of the world using new crop hybrids. New irrigation techniques for water delivery and conservation have enabled us to grown crops and raise animals where it was almost impossible several decades back, particularly in arid climates.

Today, we are at the dawn of new technological revolutions that are set to change even more dramatically the way we practice and perceive agriculture. The convergence of a technological triad (information and communication technology, biotechnology, and nanotechnology; **Figure 1**) is the hot cake in technology industry circles (Opara, 2001 and 2003a). In a recent article, we postulated an engineering and technological framework for integrating traceability into agricultural supply chain management through the application of ICT (Opara, 2002). While the debate goes on about their potential impacts and consequences on the society at large, there is little doubt that this techno-triad would have profound influences on future agriculture and environmental management. In this article, we examine briefly the technological evolution of modern agricultural, and explore some emerging challenges facing the industry. Starting with a review of the roles and impacts of mechanisation technology, we postulate the relevance and applications of nanotechnology in 21^{st}-century agriculture. Finally, we articulate a set of socio-ethical and policy issues which must be addressed to guide the development and practice of nano-agriculture.

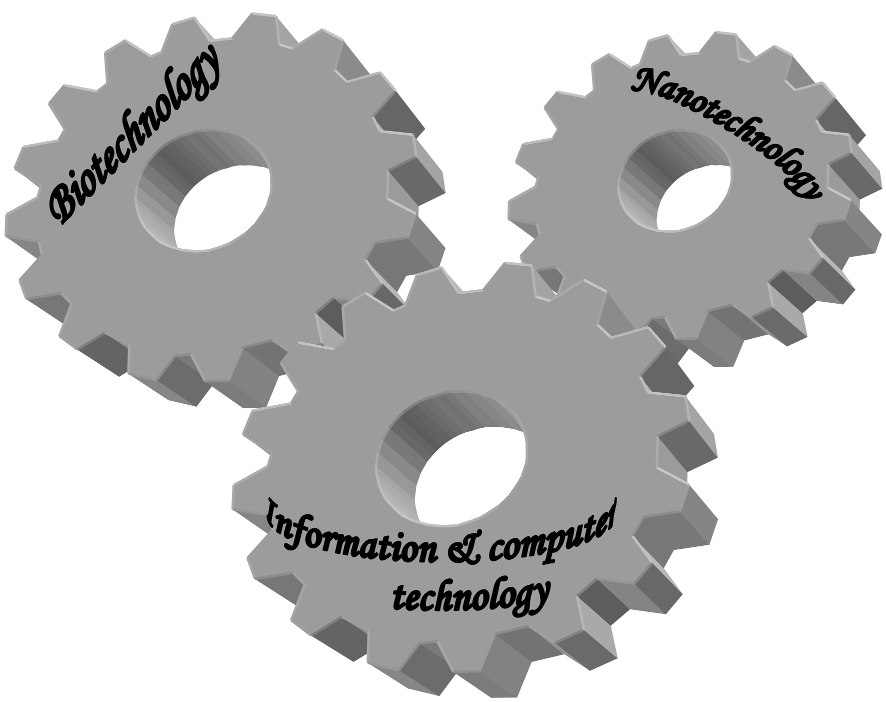


Figure 1. A technological innovation triad that is driving economic progress and wealth creation in modern economies. This drive-wheel model highlights the leveraging impact of information computer technology on the advancement of other technological innovations. (Source: Opara, 2004).

IMPACTS OF TECHNOLOGICAL INNOVATION IN AGRICULTURE

Technological innovation has become the leading strategic weapon for competitive advantage and economic progress. It is now a common parlance among business circles and goverments that those who do not innovate are destined to die. Thus, sustainable economic growth by dynamic industries and economies are characterised by widespread technological change that is supported by effective innovation systems. Technological innovation entails the creation of unique value, such as a new method of doing things, device, or service (Opara, 2002; SIAC, 2000; Smith 2000; Lievonen, 2000; IIMD, 1999)

Through the application of modern technology, agriculture has undergone extensive changes during the past century. The emergence of concentrated agricultural production has been characterized by intensive application of new production inputs such as engine-powered electromechanical devices, agri-chemicals, and the use of new and/or modified plant and animal materials (such as high-yielding breeds/varieties). As a result, new agricultural practices, handling and processing techniques have been developed to meet growing consumer demand for reliable supply of consistently high quality, safe, diverse and nutritious food products.

Patterns in consumer demand and preferences for food and other agricultural products has also been changing in recent times. In addition to the demand for consistent supply of top quantity products and services, consumers are increasingly placing new emphasis safety, functionality, and sustainability of agricultural practices. Impelled by the emergence of new food safety hazards such BSE (mad cow disease) and FMD (Footh and Mouth Disease) in livestock, and the polarized debate about the application of agricultural biotechnology, public interest on the impacts of agriculture on general human wellbeing and the environment has come under heightened scrutiny. Many consumers of agricultural products now demand for information about their origin/source as well as the method of production (in terms of sustainability and minimum impact on the environment). Many consumers increasingly demand evidence of improved animal welfare practices and as well as ‘green’ (organic) animal and plant food products. Put together, these market-pull factors have placed new demands for assurance of traceable agricultural supply chains. The foregoing development assure the future for innovative technologies to adequately address the myriad of economic and socio-cultural problems facing agriculture and farming in the 21st century and beyond.

During the past century also, agricultural productivity has increased and methods of agricultural production have changed extensively on a global scale. Changes in agricultural technology have been a major factor shaping agriculture during this period (Schultz, 1964; Cochrane, 1979; Sunding and Zilberman, 2000). An overview of the agricultural production patterns in the United States during the period 1920-1995 illustrates the magnitude of change and impact of technology in improving agricultural productivity. During this period, total harvested cropland declined (from 142 to 130 million hectares), the share of the agricultural labor force decreased substantially (from 26 to 2.6 percent), and the number of people now employed in agriculture declined from 9.5 million to 3.3 million. Despite these reductions in agricultural input per unit of land, historical data from the United States Bureau of the Census showed that total agricultural production during the same period increased by over 3.3 times (Sunding and Zilberman, 2000).

On a global scale, remarkable changes in agricultural production patterns have taken place. For instance, whereas world population more than doubled from 2.6 to 5.9 billion between 1950 and 1998, grain production per person increased by about 12 percent, and harvested area per person declined by half during the same period (Brown et al., 1999). Today, less than 5% of the population in the USA produces enough food for the entire population of over 260 million. This has been mainly possible through the application of modern laborsaving technologies for intensive on-farm mechanization, irrigation, postharvest handling and processing, and the use of improved crop varieties and animal genetics.

From a technological and engineering viewpoint, several distinct era in agricultural development can be identified and characterised as summarised in **Table 1**. Progress in agricultural engineering and technology have resulted in new machinery and process techniques for the production, postharvest handling, and utilisation of food and agricultural raw materials. In the early part of this century, these developments were largely synonymous with the terms “tractorisation” and “mechanisation” which reflected the need for increased power input to agriculture. With the evolution of Agricultural Engineering as a profession and academic discipline, the activities have grown tremendously to include information systems technology for production, handling, and processing, and improved methods for efficient and sustainable utilisation of land, water (irrigation) and other natural resources.

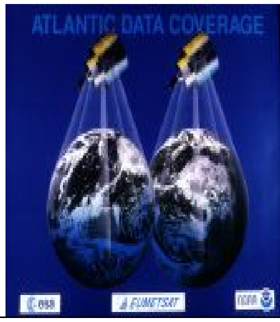
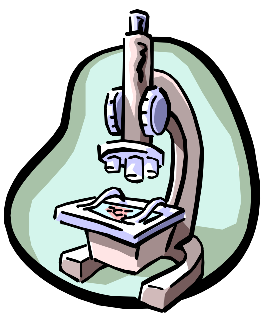
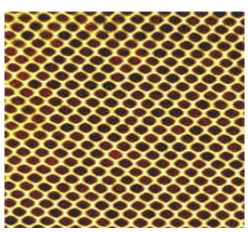
The mechanisation of agriculture was a primary mission of agricultural engineering and technology during the past century. The motivation behind this charge was summed up by Odigboh (1985): “If I dig with my hand the crust of the earth, my hands will bleed. If between my hand and the soil I interpose a spade, then out of the labour of my body, the crust is broken and my hands remain whole”. The author extended this inspiring logic as follows: “Let a machine be interposed between the man and the spade; the spade cuts, the machine labours, the field is tilled and the man is spared to turn his attention to other tasks, to higher levels of human endeavour”. Until recently, the various technical areas of specialisation within the agricultural engineering profession could be broadly classified into (a) power and machinery, and (b) soil and water. Many new specialist areas of increasing importance include postharvest and processing, sustainable energy systems, information and expert systems, and environmental engineering, which creat an overlap between the profession and the traditional engineering disciplines from which it evolved.

Faced with the danger of starvation as a result of rapidly increasing human population and low agricultural productivity per labour force, the mechanisation of agriculture helped to transform vast unproductive hectares of land into highly efficient and productive estates, and thereby removed the drudgery of manual labour. It was therefore befitting that Agricultural Engineering shared the limelight at the end of the 20th Century when Agricultural Mechanisation was named among the top 20 engineering

Table 1. Characteristics of major technological revolutions and corresponding engineering and technological impacts in agriculture.
Photo Sources: WWW.FAO.ORG; http://www.nikkiso.co.jp/e-d_kenkyu/rd_0311.html; http://www.nanoscience.gatech.edu/zlwang/

Revolution	Characteristics	Agricultural Technology/Engineering [inputs/impacts]
I- Agricultural 	Human settlement, domestication of plants and animals 	Improved hand tools, irrigation practices, storage & marketing of surplus products 
II- Industrial 	Mechanical equipment, internal combustion engines, factories and large scale processing & manufacturing, mass production of goods 	Exploitation of animal power for farming, development engine (mechanical) power, tractors, animal- and tractor-pulled implements and equipment, mechanical harvesters, irrigation dams & machinery, agricultural land drainage and reclamation, tools and equipment for product testing 
III- Chemical 	Vaccines, agri-chemicals for pest and disease management 	Spray application equipment, Nozzle technology, Veterinary technology.

Table 1 (Contd.). Characteristics of major technological revolutions and corresponding engineering and technological impacts in agriculture

Revolution	Characteristics	Agricultural Technology/Engineering [inputs/impacts]
IV- Computer & Information 	Computer technology, Information systems, calculating machines, personal computers, Internet, global positioning systems, geographic information systems, remote sensing, automation, mechatronics 	Instrumentation for automatic data acquisition and analysis (e.g instrumented spheres (IS) and environmental data recorders (EDRs)), environmental & process monitoring and control, non-destructive testing and evaluation of products, traceability technology (e.g bar-coding, scanning), precision (site-specific) farming, productivity mapping (yield & quality), GPS/GIS, remote sensing
V- Biological 	Biotechnology, gene technology, genetic modification, cloning of plants and animals 	Agricultural biotechnology, biosensors, technological innovations for imparting differentiation and desired attributes to meet the demand of consumers, closer integration of on-farm and postharvest operations due to increased yield and product lines, non-destructive testing. Bio-control.
VI- Nano 	Nanotechnology, molecular machines, mechatronics, miniaturization, micro-machines, intelligent materials, biological machines 	'smart cards' inside plants and animals for optimizing productivity, resource/input utilization and product tracebility. 'smart' machines for achieving higher precision, capacity, andtimeliness of operations. Smart micro-machines for mitigating the impacts of agricultural in the environment and ecosystems.

achievements of the past millenium (Anon, 2000; Shirley, 2000). Ranked No. 7 on the list, Agricultural Mechanisation stood alongside such other engineering feats as Electricity, Automobiles, Computers, Safe and Abundant Water Supply. Several agricultural machines such as the tractor, reaper, and the combine harvester tremendously increased farm efficiency and productivity, and thereby freed most of the population to industrialise the world.

The American Society of Mechanical Engineers reported a separate survey carried out by ranked Agricultural Mechanisation as 4th among the top 10 engineering feats of the 20th Century (Falcioni, 2000). Today, the availability of good quality cheap food in the developed parts of the world is credited to the application of improved electromechanical and chemical technologies for the production, handling, processing and distribution of food products. Arguably, one of the greatest challenges that faces society in the 21st Century is to develop technological systems that can be sustainably applied to alleviate the relentless problems of food insecurity, poverty and malnutrition that pervade in most developing countries.

SOCIO-ECONOMIC CHALLENGES FACING GLOBAL AGRICULTURE

Despite the tremendous impacts of technology applications in increasing agricultural productivity, modern agricultural faces somewhat unprecedented challenges in the years ahead, ranging from economic and social predicaments to environmental and ethical dilemmas as well as technological challenges to mitigate these challenges. First, let's discuss some of the socio-economic challenges.

Declining terms of trade affecting agriculture

One of the major challenges facing agriculture is its decline in economic importance relative to other industries such as the manufacturing and service industries. This problem is most acute in the agricultural production sector (farm-gate) which now accounts for less than 20% of the economic value of finished agricultural products at the consumer level in developed countries and over 50% in developed countries. This increasing importance of the postharvest sector (innovative handling systems and value-adding) underscores the need for a new approach to agricultural from commodity trading to integrated supply chain agribusiness. The problem of declining terms of trade facing agriculture can be exemplified by the change in milk prices in the USA. Parker (1999) showed that the cost of milk to the consumer doubled during a 15-year period (1984-1999), but the price received by the farmer remained unchanged. A synergy of factors including the continuing decline in profitability of agriculture, the huge capital investment required in modern farming, and the poor image and low appeal of farming among young men and women have continued to diminish the competitiveness of agriculture in comparison to other industries. Some may argue that current agricultural progress has become the victim of its own success by avoiding major catastrophe of massive global food insecurity that was predicted in the 19th century.

Food insecurity, poverty and malnutrition in LDcs

Despite tremendous global progress made in increasing agricultural productivity especially during the "green revolution" era, the world development literature is still replete with data on high incidence of food insecurity and poverty in many developing countries particularly in sub-Saharan Africa and parts of Asia. Twenty percent of the world's over 6 billion population (1.2 billion) live on less US$1 per day; 70% of these are rural and 90% live in Asia and sub-Saharan Africa (Thirtle et al., 2003). The World Bank (2001) poverty surveys showed that almost half of the world's population live on less than US$2 per day. Both governments and development agencies have therefore recognised the need to focus on the rural resource-poor farmers as a strategy to alleviating the problems of food insecurity and poverty facing these regions. Several researchers have also argued that since the majority of the poor live in rural areas and derive most of their livelihood from subsistence agriculture and their labour, agriculture-based technological development offers an effective approach to addressing their economic problems (Kerr and Kolavalli, 1999; Lipton, 1977).

Furthermore, a recent review of the literature by Thirtle et al. (2003) showed that investments in agricultural R&D raises agricultural value added sufficiently to give very satisfactory rates of return, in both Africa (22%) and Asia (31%), but not in richer countries of Latin America (-6%). Consequently, a 1% increase in yields reduces the number of people living in under US$1 per day poverty by six and a quarter million, with 95% of these in Africa and Asia. Despite these arguments, today's agriculture in most parts of these regions remains largely in the hands of resource-poor rural dwellers who barely make a living due to poor yield and very low returns. The socio-economic quagmire facing these farmers remains a challenge for them and the entire global community.

The problem of food insecurity is further compounded by the rising world population, which is expected to nearly double from its present 6 billion people by the year 2035, with most of the growth occurring in the developing countries. As these developing and transitional economies emerge, life expectancies are also on the rise with consumers having additional disposable income. Under this scenario, the demand for reliable and abundant supply of food is expected to increase. Concomitantly, as population continues to rise, land available for agriculture is decreasing. This further exacerbates the need for increased agricultural productivity necessary to meet the dietary and nutritional needs of the rapidly expanding population.

Economic globalisation and world trade

Globalization of the world food system is progressing at unprecedented pace, particularly with the emergence of a few multinational and transnational food chains who dominate the majority of global agrifood market. The companies increasingly source their raw materials from distant locations and a variety of sources, and using modern transportation and ICT facilitate the consumption of food products grown in locations far removed from the point of production. The globalisation of the world agrifood system through trade raises crucial challenges in terms of fair trade and competition between farmers, particularly those in developing countries who often have very limited access to improved technologies versus farmers in developed countries who commonly have access to both modern technology and government subsidy.

Environmental and ecological sustainability & welfare issues

Modern agricultural production methods have undoubtedly contributed to the depletion of natural resources and environmental degradation. Consumers are increasingly aware that modern intensive agriculture and food production practices have considerable negative impacts on the environment and ecological systems. Large-scale farm mechanisation has contributed to soil erosion, environmental pollution (Clark and Friedrich, 2000) and disruption of vital eco-systems. A significant proportion of highly vocal group of consumers (e.g. Green Peace) now demand and support the development, promotion and introduction of sustainable agriculture, leading to the growing demand for organic or 'green' foods. This increasingly important market segment expects food to be produced and processed in line with good agricultural practices, which embodies greater care of the environment and welfare of animals (Opara, 2000).

Emergence of food-related safety hazards and scares

A Euro barometer survey carried out towards the end of the last century showed that the most important issue for 68% of consumers was the safety of the food they eat. And this response was, admittedly, after the BSE crises, but before the dioxin crises in Europe (Nymand-Christensen, 1999). Numerous microbial, physical, and chemical hazards occur in the human food chain, which contribute to this major safety issue. Concerns over pesticides and other chemical residues have led to the ban of many agrichemicals used in food production and preservation. Physical contaminants (foreign materials) such as broken glass, wood, soil, plastic or metal parts such as nuts, bolts and nails can cause illness or injury to the consumer if they become embedded inside food.

Several major food-related health hazards and scares, particularly in Europe, have raised public concern on the way we practice agriculture as well as the way we handle and process food. Most notable incidents are the potential link between Bovine Spongiform Encephalopathy (BSE) in cattle and the new variant Cruetzfeldt Jacob Disease (CJD) in humans for which there is currently no cure. Food poisoning incidents and death due to *Salmonella* in poultry and eggs, *Escherichia.coli 0157* (*E.coli*) contamination of meat and meat products, fresh, minimally processed and processed fruit and vegetables, and the occurrence of other emerging food pathogens have reduced consumer confidence in the safety of our food systems.

Discovery of high levels of carcinogenous dioxins in poultry feed, some other animal feeds and in some poultry carcasses, led a major crises in the poultry and livestock industries in Belgium and several other European countries (O'Connor, 1999). Several Belgian produce including eggs, meats and dairy products were banned by many countries, forcing the Prime Minister Jeaan-Luc Dehaaene in a speech on 8th June 1999 to plea: “The animal feed producer is asked to declare on their honour whether or not they have bought fat from Verkest between January and June 1st 1999” (Food Trak, 2000). The dioxins were traced to contamination of fat and oil stores used in the production of poultry and animal feed. Though the contaminated fat was supplied to only 5.1% of farms in Belgium, it took three days to trace the poultry system alone and this was complicated further when efforts were made to forward trace it to products already in the market or consumers.

Recent outbreaks and rapid spread of Foot and Mouth Disease (FMD) in the United Kingdom, Argentina and several European countries also caused a major scare within the livestock industry and consumers, resulting in considerable financial losses. Although no threat to public health was involved, consumers began to panic and wonder about the need for massive transport and destruction of animals. According to Bayliss (2000), “the continuing tragedy of BSE and the developments on the continent have highlighted just how important traceability and branding are”.

Food quality and safety legislation

The increase in food regulations within the European Union member states following recent food scares, and the tightening of controls by other country agencies have challenged agribusiness and other life science industries to examine their production and processing practices. In addition to the European Food Authority, most member states have also established their own national Food Agency responsible for food safety. In 1996, the President Clinton signed into law the Food Quality Protection Act in the USA. As a result, regulations and guidelines have been set which cover the production and handling of food in other countries that are destined for the US market.

Impacts of genetic modification of organims (GMOs) and other food materials

The ongoing crises of confidence in the food chain, has been exacerbated by the introduction of food products derived from genetically modified organisms (GMOs) or materials. Food safety concern surrounding genetic biotechnology is controversial in both the public and scientific domain; but consumers are generally apprehensive of the uncertainty of introducing new gene sequences, which might impel or provoke other factors that are hazardous to humans and the environment. Intense public concern over the release and utilisation of GMOs, particularly in Europe, has led the EU to pass regulations on traceability and labelling of GMOs and products derived from GMOs (EU, 2000 & 2001; Byrne, 2001). These new rules will require member states to ensure traceability of GMOs at all stages of agribusiness marketing.

TECHNOLOGICAL CHALLENGES FACING GLOBAL AGRICULTURE

There are many technological challenges (and opportunities) facing agriculture in both developed and developing, which must be addressed to counter some of the socio-economic problems outlined above. Solution to these technological also provides necessary impetus for future evolution and improvement of productivity in the agricultural industry. Some of these are technological challenges have been discussed in detail elsewhere by Opara (2002a) and summarized below.

Energy utilization in agriculture

Energy input is a major constraint in agricultural modernization, especially with respect to the use of electromechanical systems. Researchers have shown a strong correlation between per-capita productivity and per-capita energy use with only minor variation in the ratio of these two parameters among countries (Klass, 1998). Increase in energy use in agriculture reduces drudgery and allows individuals to engage in higher-productivity roles and other off-farm productive activities (Opara, 1989; Denison, 1974).

The impact of improved farm power in agricultural modernization and productivity improvement is well illustrated by Clarke and Friedrich (2000): “In very broad terms a farmer using only his own labour can feed himself and 3 other persons, using draught animal power he can feed 6 people, and using a tractor he can feed up to 50 and more. It is unrealistic to think that the rapidly growing world population can be nurtured by peasant farmers, 80% of whom currently farm using family labour only”.

Modern agricultural technologies can presently provide adequate world food (Chancellor, 2001). However, the author further noted that if the great majority of the energy supplies used are from non-renewable, fossil fuel sources, the world food system becomes no longer sustainable. Based on forward projections of current food production growth rates and using currently available technologies, Clarke and Friedrich (2000) estimated that food production for 12.8 billion people in 2025 would be feasible at a time when the world population of projected to be only 7.8 billion. These trends underline the need for renewable energy sources as well as more energy efficient agricultural technologies to cope with future demand for farm power.

Managing variability

Agricultural production sites (land, soil), yield and products are inherently very variable geospatially and temporally. Accurate information on soil properties, the environment, crops, animals, processes, and their interaction is therefore needed to manage this variability in order for sustainable and economical production of goods and services that meet demanding expectations of consumers. In the future, the fusion of ICT, biotechnology and nanotechnology for agricultural applications represents an area that is set to take agriculture beyond the feats of mechanization and automation. Successful fusion of the emerging technological innovation in agriculture requires the education of individuals with good knowledge of the data needs of agriculture and who can integrate these needs into the design of innovative devices and processes. Deciding what data to capture, the most cost-effective way to collect the data, analyzing and presenting the data and integrating the information into the overall agricultural supply chain management system requires increased attention.

Profitability of small-scale farm mechanization

The majority of the human population still relies on small-scale subsistence agriculture for supply of their food, feed and fibre. Despite the resounding success achieved in medium- to large-scale agriculture, profitable mechanization of small-scale agriculture has eluded mankind. Agricultural biotechnologies such as genetic engineering have the potential to improve the situation through the availability of high-yielding materials that have resistance properties to pests and diseases. Agricultural engineering has the experience to continue to lead this charge armed with the emerging innovations such as ICT, biotechnology and nanotechnology.

Farming of marginal lands and fragile ecosystems

As world population, mainly in developing countries, continues to explode, and poverty limits their ability to access food and other resources, there is a need to increase the productivity of existing farms. Unfortunately, most of these farmlands have marginal fertility due to over-cropping and unfavorable agro-climatology. New scientific and technological inputs are needed to improve the productivity of these farms in order to raise food production in the affected areas.

Traceability of agricultural supply chains

Globalisation of the world agricultural and food supply system demands greater vertical integration within and between firms in order to adequately manage variability and remain competitive. With ever rising and changing consumer demand and consumption patterns for agrifood products, the assurance of consistent supply of top quality, safe and traceable food products remains high on the trade agenda. Developing cost-effective supply chain technologies for precision agriculture, including site-specific farming, will provide farmers and postharvest operators the necessary tools to exercise better control over yields, product quality and safety. Recent food scares and public concern over GM foods and the effects of these concerns in reducing public confidence in the safety of the human food chain have made traceability an important index of trade in agribusiness (Opara, 2002b). Traceability chains are more advanced in the livestock industry and mainly in Western Europe. There is a need for greater attention to address the traceability requirements for bulk foods such as grains, processed foods and fresh produce.

Sustainability of agriculture

Consumer demand for sustainable agricultural practices, animal welfare and waste minimisation has become imperative in modern agribusiness. This is reflected in rising global trade on eco-foods (‘green labels’) and demand for traceability from field to plate (Opara and Mazaud, 2001). However, in regions where poverty and food insecurity are major problems, there is concern that new innovations are needed to enhance yields and to control the incidence of pests and diseases under sustainable farming practices. Differentiation of foods in the market grown under different production systems is difficult based on sensory attributes, and consumers currently rely on product labeling and certification of farms by relevant agencies.

New measurement technologies are needed to detect and segregate products from different production systems such as organic versus conventional agriculture. As new indices of sustainability emerge (including environmental, water resources, land resources, air, and biodiversity) and agriculture is increasing implicated as a major cause of extensive resource depletion, engineers and engineering profession will come under more public scrutiny to include sustainability issues in curriculum and adopt sustainability as a professional ethic.

Reforms in educational curriculum and research agenda

To realize the potential opportunities that the emerging knowledge-based technological innovations offer agriculture, there is a need to integrate these innovations such as nanotechnology into the curriculum and research agenda of engineering and technoology education, particularly in discipline which support agriculture and other biological industries. The importance of the knowledge-innovation nexus and the role of education and research in generating innovative ideas are well documented (Opara, 2002a). Curriculum reforms that provide future engineers and technologists with news knowledge and skills that broaden their employment prospects into other service industries and the knowledge industry would make such academic programs and professional disciplines more attractive to young school leavers (Opara, 2003b,c).

Given the above exposition on current impacts of technology in agriculture as well as the socio-economic and technological challenges facing agriculture in the 21st century and beyond, the next section of this article will discuss nanotechnology and offer a vision for the development of nanoagriculture.

WHAT IS NANOTECHNOLOGY?

Nanotechnology is a fairly new technology and field of study. The first reference to nanotechnology was made by Richard Feynman in his famous 1959 talk entitled “There is Plenty of Room at the Bottom” in which Feynman suggested a means to develop the ability to manipulate atoms and molecules directly, by developing a set of one-tenth-scale machine tools analogous to those found in any machine shop. K. Eric Drexler in his 1986 book entitled “Engines of Creation: The Coming Era of Nanotechnology” was the first to use the term *nanotechnology*. Drexler envisioned the possibility that human-designed molecular robots could replicate themselves just about the same way cells build copies of themselves in order to reproduce.

Nanotechnology is a newly emerging field that combines fundamental science, materials science and engineering at nanometer scales (billionth of a meter) to the design and manufacture of structures and devices with dimensions about the size of a molecule. The techniques of nanotechnology also provide new powerful tools for biomolecular studies. Developments in nanotechnology have resulted from the efforts of scientists and engineers working in separate fields such as chemistry, biotechnology, photonics and microelectronics. For instance, nanofabrication integrates materials science, engineering, and biology.

Nanotechnology has been hyped among researchers, academia and industry practitioners as a revolutionary technology for the next industrial revolution. According to Vettiger et al. (2002), the nanometer will very likely play a role in the 21st century similar to the one played by the micrometer in the 20th century. **Figure 2** shows a comparative pictorial scale of natural and man-made things in nanometer and other scales. Although the term nanotechnology has many interpretations and invokes different reactions and expectations within society, it has several attributes in practice that have impacts on future agricultural engineering and technology. For instance, the behaviour of tiny electromechatronic elements may have practical applications in selective and precise application of farm inputs and site-specific data acquisition, monitoring, and transmission for real-time diagnosis and intervention.

Although it is the least developed to date among the technological triad described by Opara (2002a), the potentials of nanotechnology in diverse industries such as health, electronics and agriculture is considerable. The prospects for nanoprobes, living machinery, atom-moving devices, nanoresistors, nanowires, and nanorobots for industrial applications have been demonstrated by numerous researchers (Scientific America, 2001). Greater fusion between nanotechnology with other emerging high technologies offers greater potentials for realizing these potential technological and economic benefits (Lievonen, 2000).

Interest in nanotechnology emanates from the idea that the resulting structures may possess superior properties including chemical, electrical, mechanical and optical. Although biomedical research and defense for fighting cancer and building missiles have led investments in nanotechnology, the development of tools and techniques for characterizing and building nanostructures has far-reaching applicability across many industries including agriculture.

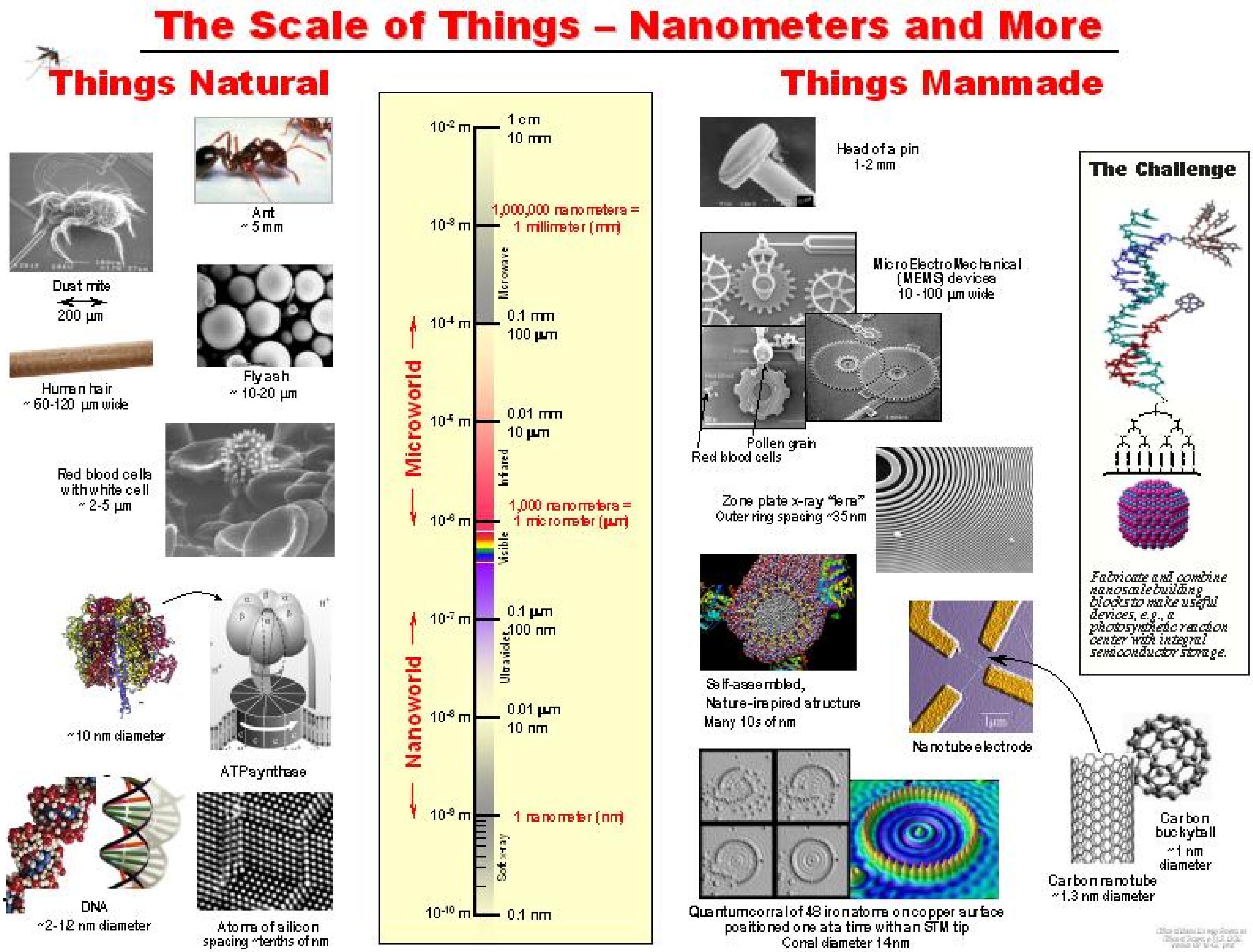
NANOELECTROMECHANISATION: A VISION OF NANOAGRICULTURE

The application of nanotechnology in agriculture will no doubt have profound impacts on agriculture as an industry and the way society views agriculture and its role in overall human welfare. In the following discussion, we contemplate some of the existing and future opportunities for nanoagriculture based on recent technological advances and future prospects.

Agrinfortronics

Agricultural is inherently heterogenous in space and time with respect to fields (soil), crops, animals, weather, etc. Data sensing, acquisition, manipulation, storage and transfer is therefore crucial in managing this variability to optimise both inputs and outputs and reduce impacts on the environment.The future of agriculture in the knowledge economy (Opara, 2002a) relies heavily on the sensing, acquisition, analysis, storage and transmission of reliable and accurate data about the plant/animal and production/handling environment to meet the demand for high yield and good quality products. This requires succesful fusion of ICT and mechatronics for agricultural

Figure 2. A pictorial representation of scales in nano- and microscale. Source: National Nanotechnology Initiative, USA http://nano.gov/html/facts/The_scale_of_things.html Accessed 3 March, 2004



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applications, which was referred to in an earlier article as agrinfortronics (Opara, 2002a). Based on advances in nanotechnology research, Vettiger et al. (2002) recently reported the development of a new scanning-probe-based data-storage concept called "millipede" that combines ultrahigh density, terrabit capacity, small form factor, and high data rate. With this new technique, the authors successfully made nanometer-sized bit indentations and pitch sizes by a single cantilever/tip into thin polymer layers, resulting in a data storage densities of up to 1 Tb/in^2 (1inch=25.4mm). Such nanotechnology has considerable applications in successful development and application of agrinfortronics.

Integration of agricultural biotechnology, bioengineering and nanobiology

Agriculture is an integral part of the wider biological industry. Given that the world of biology is at the scale of microns and below region where the sphere of nanotechnology resides, the convergence of biotechnology, bioengineering and nanobiology to solve practical problems facing agricultural is logical. Just like advances in modern agricultural biotechology have separately created staggering possibilities in crop and animal production through genetic manipulation of species, development in nanobiology are bound to impact on future agricultural technologies. For instance, Austin et al. (2002) reported the successful arrangement of control proteins on DNA within a cell; controls that make a particular cell what it is and determine the past and predict the future.

These advances open up tremendous scope for nanofabrication in modern molecular biology or agricultural biotechnology of plants and animals. Nanotechnology can thus be used to align, straighten and examine the proteins binding to DNA at ultrahigh spatial resolution. Furthermore, nanofabricated devices offer the scope for their injection into plants and animals to detect tissue parts affected by rare phenomena such as diseases, nutritient defficiency and developmental abnormalities.

Agricultural diagnostics and drug delivery with nanotubes

Progress in nanomaterials sciences and technology has resulted in the development of several devices which have potential applications in agricultural and related biological industries. For instance, nanotube devices can be integrated with other chemical, mechanical, or biological systems, and can be excellent candidates for electrical sensing of individual biomolecules. Nanotube electronic devices have been shown to function very well under certain extreme biological conditions such as saline (salty) water and have dimensions comparable to typical biomolecules (e.g. DNA, whose width is approx 2 nm) (McEuen et al., 2002; Bohr, 2002). Despite the practically difficulties in achieving reliable, rapid and reproducible nanofabrication of complex arrays of nanotubes, such devices have the potential to revolutionise site-specific and process-exact diagnosis, drug delivery and in livestock disease and health management as well as in the identification and site-specific control of plant pests and diseases.

Nanoagricultural mechanisation

Developments in electronic technology, in conjunction with mechanical technology, paved the way for automation and control of agricultural operations. Such electromechanical systems have ehanced equipment manouverability and control, environmental quantification and control such as greenhouses and animal housing. In this regard, silicon-based integrated circuits played a pivotal role, and today, the semiconductor industry has combined revenues of over 140 billion US dollars and its technical progress is exemplified by leading edge products such as microprocessors operating at 1 GHz or more, microprocessors with >100 million transistors, and memory chips with over 1 Gb densitiies (Bohr, 2002). The now famous "Moore's Law" by Gordon Moore in 1965 predicted that integrated circuit density and performance would double every 18 months, presumably from increased transistor counts and operating frequencies and reduced dimensions.

Today, the prospects of transistors at the molecular and atomic scale further enlarge the opportunities in the evolution and application of nanotechnology in the development of the next phase of miniaturised microelectromachinery for agricultural mechanisation. We consider nanoagricultural mechanisation as the revolutionary technology that extends the horizon where the current farm mechanisation (symbolised by the mechanical tractor) stops. The prospect of scaling transistors all the way down to the size of individual molecules (Bohr, 2002; Reed, 1999) and incorporating this into future agricultural machinery is an exciting application of nanotechnology which is set to have wide applications in agricultural automation and control as well as other industries.

Nanostructural basis of food product quality

Despite the existing problems of food insecurity in many parts of developing countries, global agriculture in the 21st century has undergone a remarkable paradigm shift from emphasis on quantity to quality and traceability. Consumers are increasingly demanding for steady supply of consistent quality extending from organoleptic attributes to meeting their health and nutritional needs. Measuring and predicting quality reliably is therefore an important challenge in postharvest engineering of agri-foods. Recent developments in nanotechnology applied to metrology provide new tools and insights into structure and function in materials. For instance, nanometer-sharp tips are now being used in every atomic force miscroscope (AFM) and scanning tunneling microscope (STM) for imaging and structure down to the atomic scale (Vettiger et al., 2002; Mamin and Rugar; 1992).

Despite being in its early stages, the future for nanotechnology in agriculture appears to be bright. Success in nanotechnology may result in the following (Opara, 2002a):

(a) Nanobots (miniature/micro robots the size of human blood cells or even smaller) which can be deployed by the billion, could explore every capillary and even be guided in for close-up inspections of neural details in animals during breeding and special on-farm diagnostics. Using high-speed wireless connections, the nanobots would communicate with one another and with other computers that are compiling the scan database.

(b) Nanostructures (such as smart nano-cards that collect and store data about products and process history) which can be implanted into plants and animals during growth and development to collect and transmit vital real-time data such as growth rates and physiological activities that provide clues on performance, productivity and exposure to environmental, chemical and physical hazards. Such smart nano-cards will further facilitate integrated supply chain traceability and management.

(c) Agriculture and other bio-industries inherently generate large volume of data on the environment, crops, animals, inputs and processes (hence the emergence of bioinformatics from the convergence of biological, mathematical and information sciences). Mining these data and integrating the results into an agricultural information system facilitates good enterprise management. As most farms and other agricultural enterprises are often located in rural areas distant from main communication centers, the development of high-capacity information networks will facilitate the collection, analysis and transmission of vital information, which is the backbone of precision agriculture. Boosting the carrying capacity of existing optical networks using nanowires and nanocircuits could make it possible to achieve instantaneous mining and transmission huge data for multiple applications including agriculture.

(d) The possibility of miniaturized electromechatronics that have the capacity to work under extreme conditions unsuitable for humans such contaminated sites and lethal atmospheres (such as controlled atmosphere stores for preserving foodstuff freshness). Such tiny micro-machinery could also permit greater accuracy and efficiency in site-specific and process-exact operations in the field or parts of a plant, animal or their food components.

Research & development needs for nanoagriculture

Despite the explosion in nanotechnology R&D, realisation of some of the practical industrial applications, particularly in agriculture still lies ahead in the near future. Most of the R&D is being carried in government research institutions (e.g. universities) and private sector companies. This means that much of the knowledge arising from these laboraties will be tied up to intellectual property rights of the funding organisations and this implies that it would take much longer time than anticipated to see agricultural nano-machines in farms and food handling/processing centers. Sustained adaptive research and the incorporation of nanotechnology in university SET curricula will be required to adequately develop and exploit the potentials of nanoagriculture and to impart future engineering and technology graduates with this knowledge (Opara, 2002a).

During the past two decades, precision agricultural technologies have evolved that match farm input to variation over space and time and thereby reduce residues. The use of large-scale precision agricultural technologies is developing rapidly in advanced countries but its application still remains mostly dominant in arable farming. New developments in computer, geospatial technology and remote sensing suggests a new, vast potential, but it has had limited use thus far, presumably due to high costs. However, the incorporation of nanotechnology presents yet another opportunity to develop and introduce new products which will enable miniaturized electromechanical systems to play a major role in the future of agriculture. One challenge in improving nanoagriculture will be to integrate the hardware (nanomachines), software and management tools that will take advantage of new information about agriculture. Altogether, these present new significant challenges to researchers and extension agents. Given the huge investment in budget needed for ongoing nanotechnology R&D, cost and affordability are major challenges facing the future adoption of nanoagriculture, particularly within the context of developing countries.

Another important issue associated with nanoagriculture is the prospect for improving environmental quality. It is predictable that widespread adoption of nanoagriculture in the future may be induced by environmental regulation to promote sustainable agriculture. Research is warranted to determine the application of nanotechnology in environmental management and other issues such as cost, technology transfer and intellectual property rights.

SOCIO-ETHICAL & POLICY IMPACTS

The ultimate value of technology is to improve human welfare with minimal negative impacts on the environment. In addition to the economic and welfare benefits of technology, several other factors also impact on its acceptance and use by society, including the ethical considerations. To successfully realise the prospects of nanoagriculture, it is important to anticipate public reactions so that necessary steps can be advanced to address them adequately and timely. Although nanotechnology is currently at the early developmental stage, there has been much speculation about its social, economic and legal impacts. Some argue that nanotechnology is often poorly understood; for instance, that money would cease to be of use and taxation would cease to be feasible. Nanotechnology could also elicit a strong hostile response in public opinion similar to genetic modification of plants and animals and the prospect of human cloning.

The risks posed by the power of nanotechnology extends into military weaponry and security of society. Theoretically, the techniques of nanotechnology could speed up the production of cheaper and more destructive conventional weapons as well as bioweapons of mass destruction that self-replicate. This raises social and ethical concerns about the potential that the power of nanoagriculture could be abused (i.e. nanoterrorism), thereby underlining the need to institute appropriate legal and international regulatory guidelines for the exploitation of nanotechnology.

Therefore, there is a need for constructive and satisfactory debate among stakeholders on the socio-political, economic and legal issues facing the development and use of nanotechnology in agriculture. Such debates should also assess perceptions of nanoagriculture within society as well as perceptions of public responses to nanoagriculture among stakeholders. In the ensuing debate, it needs to be borne in mind that nanotechnology presents an additional frontier for addressing some of the problems facing agriculture but not a panacea on its own.

Assessing the full societal and policy implications of nanotechnology requires the participation of a wide range of experts (including ethical, legal, health, environmental) in medium to long-term collaborative research projects. The specific research agenda should seek inputs from the myriad of stakeholders including the workforce involved in nanotechnology, consumers and other end-users, investors, policy makers and other interest groups. Molecular nanotechnology involves the risk of dealing with hazardous materials or developing potentially unhealthy ones such as nanoparticles, the possible creation of destructive, self-replicating micro-/nano robots, etc. The risks extend to potential environmental pollution and degradation.

The notion of such self-replicating nanomaterials and nanodevices generates apprehension and “grey goo” feelings about a technology that could potentially get out of control, make multiple copies of itself and unleash unstoppable chain reactions similar to cancer and the atomic bomb. Science-based assessment and unbiased reporting on the environmental impacts of nanotechnology in agriculture would assist in dispelling such perceived extreme fears. We have all learnt from public reactions towards agricultural biotechnology, particularly in Europe, that a lot of damage can occur when public trust in technology and the developers is eroded.

In a recent article on the societal issues facing nanotechnology, Roco (2003) argued that the success of nanotechnology couldn’t be determined only by doing good R&D in academic and industry laboratories. The author noted that key questions asked by technology users and public are about economic development and commercialization, education, infrastructure, and societal implications, environmental and health effects. Thus, research and development at the nanoscale, nanotechnology applications and societal implications form a coherent and interactive system, which may be visualized (**Figure 3**) as a closed loop (Roco, 2003).

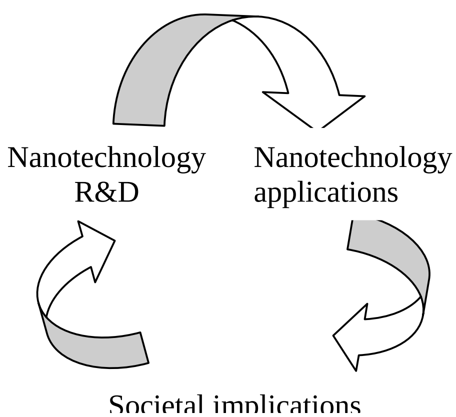

Figure 3. A nanotechnology-society closed loop (Adapted from Roco, 2003)

Roco (2003) proposed several guiding ideas for consideration when evaluating societal implications as summarized below, which are applicable to nanoagriculture:

(a) Societal implications should be judged using a balanced approach between the goals and unexpected consequences.
(b) Societal implications of nanotechnology apply in a variety of areas, including technological, economic, environmental, health, and educational, ethical, moral and philosophical.
(c) Nature is already working at the nanoscale. One needs to understand what is different when manufacturing produces nanostructured contaminants or combustion enter the environment.
(d) Each industrial field already has regulations for handling chemicals and biological materials.
(e) Societal implications have an international perspective, such as expanding fundamental knowledge of humanity and its philosophical consequences, development of markets, health concerns, international competition, and production capabilities.
(f) A significant distinction should be made between the effects that can be corrected or reversed to an acceptable level, and those that would lead to unacceptable risks.
(g) There is a complex architecture of factors, from individual creativity, organizations, technology transfer, regional and interdisciplinary interactions to economics, and international framework.
(h) Progressive advancements will be made in societal implications as the nanotechnology field better defines itself.
(i) Understanding the public acceptance of risks is important.
(j) Learning from the first industrial revolution and the previous developments.

The legal and policy framework for the development and exploitation of nanotechnology in agriculture must address issues related to intellectual properties ownership, rights and access, especially when the application of nanotechnology has the potential to impart long-term changes in the attributes of plants and animals. For instance, some plant or animal species may have significant cultural function in community life. The exploitation of such biological materials using modern technologies like biotechnology and nanotechnology must adequately evaluate the perceptions and cultural impacts on the affected community. The design of the regulatory framework will significantly affect the structure of nanotechnology industries and their impact in agriculture.

One of the lasting legacies of agricultural mechanization in regions with high rural unskilled populations that are predominantly dependent on subsistence agricultural is the negative impact on rural employment. Nevertheless, the mechanization of small fragmented farm holding is remains expensive and beyond the reach of resource-poor farmers. Despite the euphoria about the prospects of miniaturized electromechanical systems that could potentially revolutionalise the future of mechanized, the high knowledge intensity of nanotechnology and yet unknown cost regime could still place it outside the reach of small-scale resource-poor farmers, particularly in regions still near-stagnant in productivity increases during the past decades. Like the various complementary preceding technologies used in agricultural modernization (such as mechanisation, irrigation, agrichemicals, biotechnology and innovative postharvest technologies), nanotechnology must be viewed and used a means and not the end to the future of agricultural development and evolution.

CONCLUDING REMARKS

Technological innovations have had profound effects on the evolution of the agricultural sector. Nanotechnology has become one of the most exceedingly exciting disciplines in science and technology in recent times. The strong interest in nanotechnology has been generally driven by visions of a flow of new commercial applications of anotechnology that will lead to a new industrial revolution that is destined to parvade almost every industry, including the oldest one (agriculture). Both academia, governments and the private sector have shown considerable interest in the development of nanotechnology as well as its applications in diverse industries including agriculture.

Increasing globalisation, multi-functionality of agriculture, changing consumer and public perceptions and expectations about agriculture, recent food safety scares, rising demand for sustainable agricultural practices, and declining terms of trade have brought considerable pressure on agriculture. Nanotechnology represents a new technological frontier to assist in addressing these socio-economic and geo-political challenges facing agriculture and similar land-based industries.

At present, agriculture is undergoing a technological revolution as evidenced by the introduction of biotechnology, information and communication technology ICT). Developments in the ICT revolution have already spearheaded the emergence of precision agriculture, which is finding applications in various aspects of modern agriculture, ranging from precision farming, bioresource management, and supply chain optimization. We are also witnessing related processes of industrialization, product differentiation, and increased vertical integration in agriculture (Zilberman et al. 1997). These changes raise new issues and introduce new challenges. Several significant changes have been observed in agriculture from the emergence of biotechnology (Zilberman et al., 1998), and it is envisioned that the application of nanotechnology in agriculture is set to bring about more changes.

The evolution of nanotechnology suggests that the universities and private enterprise R&D companies are key players in its industrialization. The majority of the value of nanotechnology is currently embodied in specific knowledge. Therefore some of the questions, which need to be addressed as we move ahead, include the role of the farmers (particularly resource-poor farmers) as stakeholders in research related to nanotechnology applications in agriculture. This is particularly relevant given that the process of innovation and product innovation are the key to nanotechnology.

Ongoing research developments in nanotechnology represent technology-push factors that have numerous potential applications in agriculture, both on-farm and postharvest handling and processing. The convergence of a technology triad (ICT, biotechnology and nanotechnology) that is is currently driving innovation across industry sectors will provide greater opportunity for success in advancing and realising these potentials. Recent experiences gained by researchers, industry practitioners, governments and the wider society from the development of other cutting-edge technologies (such as agricultural biotechnology) should provide guidance in policy formulation and implementation in tackling the socio-cultural and legal issues which could stall the evolution of nanoagriculture.

Modern innovative technologies have had mixed impacts in addressing the productivity problems facing agriculture in many parts of the developing world, particularly in sub-Saharan Africa. The mechanisation era is now often associated with numerous machinery graveyards in failed mechanisation schemes and to date, efforts to mechanise the small-scale farm remains elusive. The debate on the benefits and demerits of agricultural biotechnology still rages on, while the problems of declining agricultural productivity and increasing food insecurity continue in many regions. The prospects for miniaturisation of electromechanical systems in agriculture offers yet another opportunity for the successful mechanisation of small-scale farms, particularly in developing countries. There is a need to instigate collaborative and farmer-oriented adaptive R&D on nanoagriculture for the transformation of traditional subsistence agriculture into modern market-oriented agribusiness. Effective communication of the goals, benefits and potential risks of nanoagriculture to users and the general public will ultimately determine the future of nanotechnology in agriculture.

REFERENCES

Anon. 2000. Agricultural mechanisation named among top 20 engineering achievements. Resource, 7(4): 17.

Austin, R.H., J.O. Tegenfeldt, H. Cao, S.Y. Chou, and E.C. Cox. 2002. Scanning the controls: Genomics and nanotechnology. IEEE Transactions on Nanotechnology, 1(1): 12-18.

Bayliss, T. 2000. Farming Online. Independent Farm Bureau News, 5 December.

Beijing Review. 2000. Will my PC be smarter than I am? January 25 (Bilingual Club), pp. 1-iv.

Bohr, M.T. 2002. Nanotechnology goals and challenges for electronic applications. IEEE Transactions on Nanotechnology, 1(1):56-62.

Brown, L. R., G. Gardner and B. Halweil. 1999. Beyond Malthus. Nineteen Dimensions of the Population Challenge, The Worldwatch Environmental Alert Series, Linda Starke, Series Editor (W.W. Norton & Company, New York).

Byrne, D. 2001. Labelling of foodstuffs – key for consumers. Round Table on Food Quality, Safety and Production, 11th July, Paris.

Chancellor, W.J. 2001. Global energy flows and their food system components. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Invited Overview Paper. Volume III.

Clarke, L.J. and T. Friedrich. 2000. Increasing food production and protecting resources. The role of agricultural engineers. Agricultural Engineering Branch, Food and Agriculture Organisation (FAO) of the United Nations, Rome, 8 pages.

Cochrane, W. W. 1979. The Development of American Agriculture: A Historical Analysis (University of Minnesota Press, Minneapolis).

EU. 2000. Working document of the Commission Services on Traceability and Labelling of GMOs and Products Derived from GMOs. Traceability document-Rev5 KM/AT/06.11.00/3.33.5.233. Brussels, 16 pages.

EU. 2001. Commission improves rules on labelling and tracing of GMOs in Europe to enable freedom of choice and ensure environmental safety. IP/01/1095. European Union, Brussels, 6 pages.

Falcioni, J.G. 2000. 20TH Century engineering feats. Editorial. Mechanical Engineering, 122(1):4.

Food Trak. 2000. Dioxin in Belgium – could Food Trak have saved the day? http//www.farmonline.com/…/Dioxinbelg. Accessed 18 December, 2001.

IIMD, 1999. World Competitiveness Handbook. International Institute for Management Development, Switzerland.

Klass, D.L. 1998. Biomass renewable energy, fuels and chemicals. Academic Press, San Diego, CA, 651 P.

Kerr, J. and S. Kolavalli. 1999. Impact of agricultural research on poverty alleviation: conceptual framework with illustrations from the literature. EFTD Discussion Paper No. 56. Impact assessment and evaluation group, IFPRI, Washington, D.C.

Lievonen, J.T. 2000. Innovation opportunities form fusing high technologies. Tech Monitor (Sept-Oct), pp. 22-28.

Lipton, M. 1977. Why poor people stay poor? Urban bias in world development. London: Temple Smith.

Mamin, H.J. and D. Rugar. 1992. Thermomechanical writing with an atomic force microscope tip. Applied Physical Letters, vol. 61: 1003-1005.

McEuen, P.L., M.S. Fuhrer, and H. Park. 2002. Single-walled carbon nanotube electronics. IEEE Transactions on Nanotechnology, 1(1): 78-85.

Nymand-Christensen, J. 1999. How should consumer concerns be addressed? Teagasc, Irish Agriculture and Food Development Authority. Accessed 18 December, 2001. http://www.teagasc.org/publications/agrifood1999/paper11.htm.

O'Connor, B. 1999. Disease impact. Animal Health Forum June, Alberta Agriculture, Food and Rural Development. Airdrie, Canada.

Odigboh, E.U. 1985. Mechanisation of cassava production and processing: a decade of design and development. Inaugural Lecture Series No. 8, University of Nigeria, Nuskka, 52 pages.

Opara, L.U. 1989. Computer-based model for selective mechanisation of Nigerian agriculture. Unpublished MEng thesis, University of Nigeria, Nsukka.

Opara, L.U. 2000. Market-pull factors influencing consumer perceptions of quality (or quality assurance for whom?). Proceedings of the 2nd ASEAN Postharvest Technology Seminar, Ho Chi Minh City, ACIAR Publication No. 100.

Opara, L.U. 2001. Historical evolution and tasks for Agricultural Engineering in the new millenium. In: Kosutic, S (Ed.). Proceedings of the 29th International Symposium on "Actual Tasks for Agricultural Engineering", , Zagreb, pp. 1-20.

Opara, L.U. 2002a. Agricultural Engineering education and research in knowledge-based economy. In: Kosutic, S (Ed.). *Proc.* of the 30th *International Symposium on Agricultural Engineering*, Zagreb, Croatia, pp. 33-46.

Opara, L.U. 2002b. Engineering and technological outlook on traceability of agricultural production and products. *Agricultural Engineering International: the CIGR Journal of Scientific Research and Development*, Vol. IV: 1-12.

Opara, L.U. 2003a. Traceability in agriculture and food supply chains: a review of basic concepts, technological implications, and future prospects. *Food, Agriculture & Environment*, 1(1): 101-106.

Opara, L.U. 2003b. 'From Farmers to Blue-Colar Professionals': Agricultural Engineering students' perspectives on their career prospects, critical skills, and discipline name change. World Transactions on Engineering and Technology Education 2(3): 399-402.

Opara, L.U. 2003c. Image is Everything: Undergraduate students' contributions towards better understanding and improvement of public attitudes and perceptions of Agricultural Engineering. World Transactions on Engineering and Technology Education 2(3): 457-460.

Opara, L.U. 2004. Outlook on Agricultural Engineering Education and research and prospects for developing countries. Outlook on Agriculture, 33(2): 101-111.

Opara, L.U. and F. Mazaud. 2001. Food traceability from field to plate. Outlook on Agriculture, 30(4): 239-247.

Parker, D. 1999. How should we farm? Kencove Farm Fence. http://www.kencove.com. Accessed 19 December 2003.

Reed, M. 1999. Molecular-scale electronics. Proc. IEEE vol. 87, pp. 625-658.

Rocco. M.C. 2003. Broader societal issues in nanotechnology. Journal of Nanoparticle Research, 5:181-189.

Schultz, T. W., 1964. Transforming Traditional Agriculture. Yale University Press, New Haven, CT.

Scientific American. 2001. Nanotech: the science of small gets down to business, Vol. 285, Number 3.

Shirley, M. 2000. Agricultural mechanisation among century's top engineering achievments. Institutions of Agricultural Engineers – Newsletter (Spring), 3-5.

SIAC, 2000. New Zealanders: innovators to the world, turning great ideas into great ventures. A proposed innovation framework for New Zealand. Science and Innovation Advisory Committee, Wellington.

Smith, G. 1999. Australia's innovative environment compared with USA experience. Industrial Innovation Working Group, Canberra, 9 pages.

Sunding, D. and D. Zilberman. 2000. The Agricultural Innovation Process: Research and Technology Adoption in a Changing Agricultural Sector. In: *Handbook of Agricultural Economics.*

Thirtle, C., L. Lin and J. Piesse. The impact of research-led agricultural productivity growth on poverty reduction in Africa, Asia and Latin America. World Development, 31(12): 1959-1975.

Vettiger, P., G. Cross, M. Despont, U. Dreschler, U. Durig, B. Gotsmann, W. Haberle, M.A. Lantz, H.E. Rothuizen, R. Stutz, and G.K. Binnig. 2002. The "Millipede" – Nanotechnology entering data storage. IEEE Transactions on Nanotechnology, 1(1): 39-55.

World Bank, 2001. World Development Report 2000/01 Attacking Poverty. New York: Oxford University Press.

Zilberman, D. and A. Heiman. 1997. The value of economic research. American Journal of Agricultural Economics 79(5), 1539–1544.

Zilberman, D., C. Yarkin and A. Heiman. 1998, Agricultural biotechnology: Economic and international implications, Mimeograph, Department of Agricultural and Resource Economics, University of California, Berkeley.

Zilberman, David, David Sunding and Madhu Khanna. 1997. The changing nature of agricultural markets: Implications for privatization of technology, information transfer, and the role of land-grant research and extension, In: Steven Wolf (ed.), Privatization of Information and Agricultural Industrialization. CRC Press, Boca Raton, FL.
