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FERTILIZER PRODUCTION INNOVATIONS TO MEET CUSTOMERS' NEEDS IN THE FUTURE

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This 50th anniversary meeting of the International Fertilizer Industry Association (IFA) Technical Conference is one of those special occasions that is commonly celebrated by reflecting on past accomplishments and speculating about future challenges. Other presentations at this meeting celebrate technical achievements previously made by the fertilizer industry. IFDC was invited to speculate about challenges that might be encountered in the future and possible solutions. Of course, attempts to anticipate future events are, at best, only conjecture based on trends that are perceived to be important at the present time. However, a 50th anniversary that occurs near the beginning of a new century seems to be a particularly good time to speculate about the future.

The approaching transition from the 20th to the 21st century has stimulated numerous discussions and debates concerning challenges that await the world in the future. Several trends and issues are recognized that could significantly impact the fertilizer industry if they continue in the direction seen at the present time. Some of these trends and issues will directly impact customer needs and methods that can be used to manufacture fertilizers. Other factors will indirectly impact the industry by influencing agricultural practices and the types of crops that farmers will grow.

None of the trends or issues discussed in this paper are newly developed; you may have read or heard about them elsewhere. Many of the challenges that the fertilizer industry will confront in the future will not be solved by technology; many issues may require other actions to change existing governmental policies and cultural habits. Four trends or issues are discussed in this paper; these are listed below:

> **Increasing World Population —** Increased world demand for food and other agricultural products is expected to increase the demand for fertilizers and more intensive use of resources.
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> **Increasing Concerns About Environmental Impacts of Fertilizer Production and Use —** More stringent and globally applied environmental standards will require changes in fertilizer manufacturing technologies and agricultural practices.
>
> **Changing Availability of Raw Materials —** Decreased availability of materials from traditional sources and changing sources of supply could require changes in manufacturing technologies to cope with the properties and costs of raw materials.
>
> **Increasing Number of Products Generated by Advances in Biotechnology —** Availability of genetically engineered plants and animals, with properties more attractive to farmers, could influence crop preferences and change the quantities and types of fertilizers needed.

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Increasing World Population

A prominent trend that has been evident for several decades is that world population is increasing rapidly and shows no evidence of stabilizing until after the 21st century. The increased population projected for the next century will consume significantly more food, fiber, fuels, medicines, chemicals, and other materials derived from agricultural crops than are currently being produced. Satisfying increased demand for agricultural products will require increases in agricultural production.

The United Nations **[1]** estimates that the mid-1996 world population was 5.77 billion, and the population growth rate for the period 1990-95 was 1.48% per annum. These figures show a slightly decreased rate of growth from the 1994 U.N. estimate of 1.57% per annum. At the currently estimated rate, world population is increasing by 81 million each year. This compares with an estimated 87 million persons added each year between 1985 and 1990, the peak period in the history of population growth. The 1996 data showed a very noticeable decline in fertility levels for Asia and Latin America where rates dropped from about five births per woman in 1970-75 to less than three births per woman in 1990-95. However, fertility levels in sub-Saharan Africa remain high. In 17 countries, fertility rates equal or exceed six births per woman and show little sign of decrease.

The United Nations projects that world population will be 6.09 billion in 2000, 8.04 billion in 2025, 9.36 billion in 2050, and 10.37 billion by 2100. If growth rates do not change, world population is expected to stabilize at slightly less than 11 billion after 2200. Most of the population increase will occur in the developing regions of Asia, Africa, and Latin America. Only one (United States) of the projected ten most populous nations in 2050 (listed in the following table) is not in one of these regions.

Nation	2050 Population (millions)	Percent of 2050 World Population
India	1,533	16.4
China	1,517	16.2
Pakistan	357	3.8
United States	348	3.7
Nigeria	339	3.6
Indonesia	318	3.4
Brazil	243	2.6
Bangladesh	218	2.3
Ethiopia	213	2.3
Iran, Islamic Republic of	170	1.8
Totals for the 10 nations	5,256	56.1

Analyses of projected population trends indicate that the food production levels of the past three decades will not support the requirements of the population that is expected in the next three decades. One estimate indicates that meeting food demands in 2025 will require that production of food crop grains be increased to nearly twice the current grain production levels **[2]**. In addition, production of other crops must increase by 40%-45%. The projected rate of growth in food production needed is greater than what has been accomplished over the past 25 years using the Green Revolution technologies.

In past decades, the world was able to meet increases in food demands by increasing crop production. During the 1961-90 period, when the world population was rising at a rate of 1.9%, food production grew 2.8% per year. Primary factors in increased food production were expansion of cultivated lands, use of high-yielding varieties, increased applications of fertilizers, irrigation, and the use of crop protection chemicals. Continued reliance on this approach is not expected to be sufficient for future needs.

The amount of arable land on which to grow food is more limited than it was 30-50 years ago. The amount of land that can be satisfactorily used to expand agriculture has been decreasing worldwide as larger areas have been, and will continue to be, used in satisfying growing demands for residential, industrial, and urban expansion. Use of water for nonagricultural purposes will increase as the numbers of industrial and domestic consumers grow; water for irrigation will be less available and more expensive than in the past. Water scarcity problems are expected to be particularly serious in Africa and Asia, where the need for increased food production will be greatest **[3]**. Because of these limitations, most of the increased food production needed in the next century will require intensified crop production to increase yields from the land and water resources that are available. Intensification of agriculture will require significant shifts in policies, improved agricultural practices, and increased inputs of fertilizers to replace nutrients removed from the soils with harvested crops **[4]**.

Reliance on traditional fertilizers alone to provide needed plant nutrients may not be sufficient. Projections of fertilizer supply-demand balances by Bumb and Baanante **[4]** show that fertilizer production will meet or slightly exceed projected demands in 2000. But, if fertilizer production capacity does not expand after 2000, global demand will exceed supply by 51 million tons by 2020.

Proponents of the so-called Doubly Green Revolution point out that diverse nutrient sources should be available to aid farmers in adequately supplying and managing nutrient inputs to their crops **[5]**. Although priority can be given to the use of mineral fertilizers, agricultural researchers should seek methods that farmers can use to manage nutrient inputs needed to achieve and maintain high yields. Proposed options that could reduce demand for manufactured fertilizers, if successfully developed and adopted, include:

- Improving the status of soils by recycling harvest residues, composting byproducts, or adding composted urban waste and animal manure.
- Using nitrogen-fixing plants.
- Using new fertilizers, e.g., reprocessed organic fertilizers from animal wastes and micro-encapsulated fertilizers that release nutrients according to temperature and humidity.
- Providing fertilizer inputs in small doses to avoid leaching and atmospheric losses.
- Recovering and recycling nutrients from deep in the soil profile and root systems.

Several of these alternative nutrient sources could provide opportunities for the fertilizer industry to develop new products and manufacturing technologies. Improved technologies will be needed to economically convert agricultural and industrial wastes into fertilizers. Intensification of existing farming methods will require products and practices that improve nutrient utilization efficiencies. Numerous possibilities that have been considered by agricultural and fertilizer researchers in the past have not been developed because of unfavorable economic or technical problems. However, rapid advances in many fields (e.g., information processing, biotechnology, materials sciences) are generating an almost continuous stream of new techniques and products. Applications of these techniques might provide the necessary breakthroughs to develop products needed in the future, such as those listed below:

- Fertilizers with high organic matter and adequate nutrient contents made by enhancing nutrient levels of composted materials with mineral fertilizers.
- Controlled release fertilizers that are economically and agronomically suitable for use on commodity crops.
- Improved inhibitors for chemical fertilizers that will reduce the losses of applied nitrogen by ammonia volatilization and/or nitrate leaching.
- Fertilizers with physical and nutrient characteristics tailored to the needs of developing «high technology" agricultural practices.

Increasing Concerns About Environmental Impacts of Fertilizer Production and Use

Fertilizer Production

There is little doubt that fertilizer production and use has been significantly affected by concerns that industrial and agricultural activities potentially pose threats to the environment and human health. In the past decade, numerous reports and discussion papers have described the impacts of increasingly stringent environmental regulations and quality standards **[4, 6, 7, 8]**. Proceedings from IFA Technical Conferences have described the advances made by the industry to remedy many problems. IFDC-sponsored workshops **[9, 10]** and state-of-the-art reviews **[11, 12, 13, 14]** provide additional viewpoints and descriptions of environmentally oriented technologies to reduce waste and improve environmental quality.

The intensity and focus of public concern about environmental issues have varied from highly alarmed to apathetic, particularly depending upon world and site-specific economic and social conditions at the time. However, concerns about environmental issues never completely disappear, nor is there any indication that they will lessen in the future. For example, the U.S. EPA Toxic Release Inventory for 1995 showed that total air and water emissions of ammonia and nitrate compounds were the second and fourth highest, respectively, among 643 industrial chemical emissions included in the inventory. More nitrate compounds were reported as water discharges than any other chemical on the list, and fertilizer manufacture was cited as the primary source of the releases **[15]**.

New technologies for more effective elimination of pollution at fertilizer production sites might come from sources outside the fertilizer industry. The concept of «green chemistry» is developing into a strategy that many other chemical producers will use in designing and operating their installations. Using this approach, the entire life cycle of production is examined to develop strategies and methods for more efficiently producing useful products with less waste or preferably with no waste. According to Paul V. Tebo, Vice-President for Safety, Health, and Environment at DuPont, in an address to the first Green Chemistry & Engineering Conference, held in Washington, D.C., in 1997, businesses that apply green technology will be able to become more profitable **[16]**. Tebo indicated that over the next 25 years green chemistry will focus on the following areas:

- Reducing emissions and waste, with a goal of zero emissions.
- Efficiently using materials, energy, and water, including a substantial use of recycled and reused materials and a growing reliance on renewable resources.
- Developing inherently safer processes, distribution methods, and products.
- Reducing total system impact through tools such as life-cycle assessment.
- Creating significant customer and societal value per unit of resources extracted.
- Creating significant shareholder value.

Successes in these activities could change the standards by which all chemical producers will be judged. DuPont found it was critically important to set a goal of zero-emission operations. Tebo explained, «When you focus on zero you normally get much closer to it than if you focus on incremental reductions.» With this goal, DuPont reduced waste production at one of its nylon plants to the extent that it will close the plant’s waste treatment facility in late 1997, thereby saving $250,000 annually and eliminating the need to spend US $20 million for an upgrade of their facility.

Future adoption of a zero-emission standard by environmental regulators will require that fertilizer producers modify production operations to increase conversion efficiencies and minimize secondary reactions during the production of ammonia, nitric acid, sulfuric acid, phosphoric acid, and compound fertilizer products. More efficient scrubber systems will be needed to capture and recycle any gaseous compounds that might escape the reactors. Highly efficient containment systems will be needed to capture liquid effluents for treatment or recycling.

Considering the advances being made in biotechnology, many pollution and waste treatment operations could be biologically based. Technologies being investigated by the Tennessee Valley Authority (TVA) at the Environmental Research Center (the former National Fertilizer and Environmental Research Center) include biofilter reactors that use confined microbiological systems to convert pollutant gases and liquids into harmless forms and constructed wetlands that remove heavy metals, organic compounds, and ammonia from industrial and municipal wastewaters. Wastes that contain low levels of plant nutrients would be particularly suited for treatments by biological technologies. More research and development is needed to make these technologies economically and operationally feasible. Processes are needed that will make it possible and practicable to recover metals and other valuable pollutants for use in other applications.

Environmental problems associated with production of phosphate fertilizers are particularly challenging. Phosphate rocks contain varying low concentrations of several elements that are potentially harmful to human health including arsenic, cadmium, chromium, lead, mercury, and uranium. Unfavorable economic considerations presently impede the adoption of technologies that have been developed to remove cadmium from phosphate rock or phosphoric acid **[13]**.

Increased publicity and public concern about potential hazards associated with fertilizers and the crops grown using them might require that the industry of the future provide products that are essentially free of cadmium, arsenic, lead, mercury, uranium, and any or all of the other toxic metals. New technologies will be needed to find ways to overcome existing economic and technical barriers. Advances in polymer synthesis technology might provide ion exchange resins or semipermeable films to develop processes that will permit more efficient removal of metal contaminants from phosphoric acids. Advances in solar energy technology might provide economical furnaces to use in processes for removing cadmium by calcination of phosphate rock.

Radioactive impurities in phosphate rock and products pose problems because of the potentially carcinogenic hazards associated with chronic exposure to low-level radiation. During production of phosphoric acid by sulfuric acid-based methods, much of the uranium contained in phosphate rock feeds reports to the acid product, and radium tends to follow calcium to the phosphogypsum byproduct. Radium also will be generated in P-containing fertilizers as a consequence of the natural decay of uranium contained in phosphate compounds. Uranium and radium are also found in phosphate rocks used for direct application or for producing nitrophosphates.

Uranium can be removed from phosphoric acid by solvent extraction technology and other methods developed when demand for uranium to produce weapons and nuclear power plant fuel kept uranium prices high enough to justify recovery costs. Radium can be removed from phosphogypsum by repulping the gypsum and coprecipitating radium with barium sulfate **[17]**. These approaches are considered neither technically nor economically attractive at present. Future environmental regulations may require that more cost-effective technologies be developed to ensure that uranium and/or radium in phosphate fertilizer products or wastes do not present hazards to fertilizer users and the general public. However, development of practical technologies may be complicated because of the problems in disposing of the concentrated radioactive materials that would be generated.

The problem of phosphogypsum disposal has been the subject of considerable research and development to find satisfactory options to the current disposal or containment practices. The Florida Institute of Phosphate Research (FIPR) **[18]** has sponsored work to develop a thermal process for producing sulfur and aggregate from phosphogypsum. FIPR also has demonstrated a technique for using phosphogypsum as roadbed material for highway construction. Work on the roadbed project was stopped when the U.S. Environmental Protection Agency (EPA) banned the use of phosphogypsum in construction after concluding that radon released from decaying radium in the material posed unacceptable hazards to the public. Recently, an FIPR study found that results of the EPA assessments may have overstated the risks involved, and FIPR has requested that EPA permit use of phosphogypsum in road construction **[19]**.

Even if acceptable construction uses for phosphogypsum are developed, they might not be applicable worldwide, nor would they probably provide sufficient capacity to dispose of existing and future gypsum production. Continued research is needed to potentially develop means to profitably use phosphogypsum produced at the present time and in the near future. In the long term, it would be very desirable to develop technologies to manufacture phosphate products that do not involve co-producing gypsum that cannot be satisfactorily used for various agricultural and industrial applications. If alternatives to nitrophosphates are needed, products such as the 20-10-0 urea superphosphate (USP), described by Limousin et al. **[20]** at a recent IFA Technical Conference, might be considered. The USP process avoids producing phosphoric acid and is claimed to produce zero liquid effluents and near zero fluorine emissions. Reported results of agronomic testing with maize and rice showed higher yields with USP than with equivalent applications of standard NP products.

Fertilizer Use

Recent environmental concerns about the use of fertilizers have focused on atmospheric emissions of ammonia and nitrogen oxide gases that are generated by natural processes in soils, on pollution of drinking water supplies by leaching of nitrate into the ground water, and on surface water pollution by runoff of nutrients from cultivated fields into local streams and lakes **[21, 22, 9, 10]**. Anticipated increases in fertilizer use to help satisfy growing demands for food and other agricultural products will potentially accentuate the environmental problems where N is not managed well.

Improved agricultural practices are providing some relief to these problems and will likely continue to do so in the future. Precision agriculture technologies, which allow variable rate fertilizer application within a field so that nutrients are placed to more closely meet crop needs, can increase nutrient utilization efficiencies and minimize nutrient losses. Because of costs, these high technology practices are currently best suited for large farming operations and higher valued crops. Farmers who do not use these methods will need more assistance from fertilizer producers and other agencies in minimizing adverse environmental impacts and conserving nutrient resources. Fertilizer products that supply nutrients more efficiently and effectively are needed. A primary need will be controlled nutrient availability fertilizers that are economically suited for use on commodity food and fiber crops.

The organic chemical and pharmaceutical industries have made significant advances in using molecular modeling methods to design chemical compounds with specific functions. Applications of technologies developed by these industries could be exploited to find better coating materials to manufacture controlled release fertilizers. For example, crystallizable polymers that exhibit abrupt temperature-dependent changes in their physical properties are being evaluated as coatings to protect seeds from fungal attack in cold, wet soils **[23]** and as controlled medication delivery systems **[24]**. This technology may be applicable to designing controlled nutrient release fertilizers. Advances in technologies under development in biology and synthetic chemistry could be combined to aid in designing improved nitrification and urease inhibitors.

Changing Availability of Raw Materials

Increased production and transportation of fertilizers to meet the larger demands for food and fiber expected in coming decades will increase the consumption rate of finite, nonrenewable supplies of natural gas and other fuels, phosphate rock, potash, and other nutrients needed for current manufacturing technologies for fertilizer products. The more pessimistic analysts have warned that the world is consuming its supplies of nutrient resources and that increased use of fertilizers will further aggravate the problem. Other analysts report that worldwide supplies are adequate and additional resources will become available when economic conditions are favorable. In any case, future improvements in resource recovery and utilization technologies are needed to prevent increases in prices that could make fertilizers unavailable to the less wealthy regions where increased food production will be most needed.

Issues affecting future supplies of phosphate rocks have been reviewed by Van Kauwenbergh **[25, 26]**, Rahm **[27]**, Buckley **[28]**, and others. The available information indicates a change will occur in the worldwide supply of phosphate rock in about 10 years. Beyond that time, it is expected that there will be declines in the quantity of rock produced from Florida deposits, which historically have been one of the world's primary sources of quality phosphate rock. Fertilizer manufacturers and consumers who rely on rock, acid, or other phosphate products from Florida deposits will have to adapt production operations to these changes or find other sources. Production from deposits in Africa, Asia, Latin America, and other regions will have to be increased to satisfy world demands.

Considerable research is underway to find ways to maintain production of acceptable quality phosphate rocks and fertilizer products from Florida's future resources **[18]**. Work to develop improved technologies for efficiently recovering phosphate values from ores with higher impurity contents includes investigations to improve existing beneficiation and phosphoric acid production processes and reviews and technical evaluations of alternative processes such as the use of bacteria as modifiers and/or collectors in the flotation of dolomitic phosphate rock (which is not presently recovered) and the use of biological processes to solubilize the phosphate in low-grade ores **[29]**.

Breakthroughs in any of these efforts would extend the life of phosphate production from Florida resources.

Fertilizer production technologies developed in efforts directed primarily at Florida phosphate rock may be applicable to other phosphate rock sources. As producers who have relied primarily on Florida deposits shift to other raw material sources, existing production technologies may have to be adjusted or modified to match the compositions and properties of the new rock supplies. In some cases these will be minor changes. Production operations that will use lower grade phosphate rocks with different impurity assemblages will require new beneficiation and chemical production technologies. Changes in rock production and transportation economics may become more significant drivers of technological development than changes in rock properties. Innovative, zero-waste technologies would be needed to gain maximum economic utilization of the phosphate contained in the rock.

There has long been interest in direct application of phosphate rock to supply P nutrients to crops, thereby avoiding some of the costs of chemical fertilizers **[30, 31]**. As world reserves of high-grade, relatively lower cost phosphate rock become depleted, economic factors may make direct application of low-grade, low-quality, reactive phosphate rock more attractive. Successful results from ongoing research to develop biological methods for increasing rock solubilization could make the direct application of phosphate rocks inoculated with microbial agents a practical source of P nutrient **[32]**.

Recent evaluations of natural gas resources that will be available for ammonia production in the future have been very optimistic **[33, 34, 35, 36]**. Analysts expect to see continuing growth of gas production in most regions of the world, especially in the Middle East. Carson **[36]** reported that Enron Corporation’s estimates of proven reserves' life increased from 53 years in 1976 to 65 years in 1996. Additional ammonia and urea plants are expected to be constructed in gas-rich areas to take advantage of the availability of reliable low-cost natural gas supplies. Analysts say that the pace of future pipeline construction will increase. Production of liquefied natural gas (LNG) and the infrastructure needed to transport LNG also are increasing **[36]**.

Opposing this optimistic view of future natural gas resources is the fact that the expected increase in world population will result in increased energy consumption, and ammonia producers will have more competition for the natural gas that is available. Environmental considerations are making natural gas more attractive than coal and oil as a fuel for electric power generation. According to Enron **[36]** consumption of coal and oil by power plants is expected to grow about 3.5% and 3.2%, respectively, per year between 1996 and 2015. Consumption of natural gas and LNG for electric power production is expected to grow about 5.7% per year in the same period. Environmental issues also will affect vehicle fuel choices. Batelle technology experts predict multi-fuel automobiles that operate with a variety of fuels, including natural gas, could become commercially practical within the next 10 years **[37, 38]**.

Increases in natural gas consumption may develop as supplies of crude oil are depleted. Ivanhoe **[39]** points out that discoveries of new oil-producing fields reached a maximum in 1962. Since then, the global discovery rate has dropped in all regions. Although annual production from known fields fluctuates with demand over short periods, the overall trend since the 1940s has been upward. Ivanhoe projects that crude oil production will peak in about 2010 and will then begin to steadily decline. Alternative fuels will be needed to supply the world’s energy demands.

Synthetic oil produced from natural gas could become an important alternative fuel as liquid hydrocarbon resources are depleted. Recently announced improvements in Fischer-Tropsch technology have increased efficiencies and lowered the costs for synthesizing oil from natural gas to the point that commercial operations are considered practical. ARCO, Marathon Oil, and Texaco have licensed technology developed by Syntroleum Corporation. Exxon Corporation is developing a process that could produce up to 100,000 barrels daily of crude-oil substitute from natural gas and plans to build a production plant in Qatar. Sasol, Ltd., has teamed with Statoil to develop seaborne production plants that can be towed to off-shore gas wells. The U.S. Energy Department is in the process of selecting an oil company to participate in a joint effort to develop commercial plant designs for the gas-to-oil technologies **[40]**.

If the current trend continues, synthetic oil production could compete with the fertilizer industry for available gas supplies. The estimated excess by which increases in gas reserves have outpaced growth in gas consumption for the past two decades would provide enough synthetic oil to meet the world’s oil demand for about 29 years. If gas reserves are less than expected or consumption is greater than expected, nitrogen fertilizer production technologies with higher conversion efficiencies might be needed to avoid large price increases. Use of coal rather than natural gas might become more economically feasible.

While the main emphasis of this section is on fuel availability for production processes, increased costs of fuel for transportation to move fertilizer within countries and around the globe may eventually have a profound impact. Increased transportation costs for sea and overland transport may affect trade patterns and use. Increased fuel costs should also serve to further concentrate production sites near fuel and raw material sources and focus production on products with high-nutrient contents, reducing transportation costs on a contained nutrient basis.

Increasing Number of Products Generated by Advances in Biotechnology

In addition to a growing demand for products due to an increasing global population, the fertilizer industry of the future is likely to be impacted by developments from the biotechnology industry. Recent advances in biotechnology suggest that a continuing generation of new biological products will have profound impacts. Dr. Robert F. Curl, 1996 Nobel prize-winning chemist from Rice University, has said, «This was the century of physics and chemistry, but it is clear that the next century will be the century of biology» **[41]**. According to Dr. Jerry Caulder of Mycogen Corporation, «Biotechnology is doing two things: converting agriculture from chemistry-based to biology-based, and taking a huge pesticide industry and a huge seed industry and making one industry out of them.» Caulder believes that the current development of pest- and chemical-resistant products is the first step leading to bigger opportunities **[42]**. Future accomplishments from current research and development programs are expected to generate impressive payoffs, particularly in the fields of medicine and agriculture.

Products that are already reaching the market include seed for cotton, corn, and potato varieties that have been genetically engineered to have improved resistance to insects and seed for herbicide-resistant soybeans, cotton, and corn. A Monsanto survey of farmers who used their Bollgard cotton seed in 1996 found that 80% were satisfied or very satisfied. Responses varied from region to region due to unexpected high bollworm infestations in some areas. Cotton growers reported an average 7% improvement in yield **[43]**.

In addition to incorporating pest-resistant genes in traditional crops, other applications of biotechnology are aimed at developing agricultural crops that are designed to have specific nutritional, processing, taste, or handling qualities. Mycogen is investigating technologies to enhance the nutritional characteristics of livestock feed and develop high-starch corn hybrids that can be grown for ethanol production **[42]**. In work at the Carnegie Institute, a gene for making plastic was inserted into *Arabidopsis*, a type of mustard plant. Monsanto is working to commercialize the concept so that farmers can grow plants that make enough plastic materials to reduce the dependence on oil for chemical production **[41]**. Scientists are searching for the gene that produces the enzyme that controls cellulose formation in plants. By genetically boosting the enzyme level, researchers hope to create trees that have much higher cellulose contents and lower amounts of other cell wall components. Using these trees for making paper would give higher yields and reduce the amounts of wastes generated **[41]**.

Genetic engineering is being used to modify plants so that they can be grown on soils where growth may be inhibited. Researchers in Mexico have produced transgenic tobacco and papaya plants that can tolerate higher levels of solubilized aluminum in acid soils. The plants were engineered to over express a citrate synthase gene from *Pseudomonas aeruginosa* to increase the release of citric acid from plant roots. The citric acid is believed to improve tolerance for soils that have high-aluminum contents by sequestering aluminum ions and preventing aluminum uptake. The researchers reported that the modified plants grew normally in the presence of up to 300 micromolar soluble aluminum. Control plants did not survive when exposed to aluminum levels of 50 micromolar or higher. Further research is planned to attempt to increase the aluminum tolerance of important crop plants (rice, maize, and sorghum) so that the plants can be grown more effectively in acidic soils **[44]**. Other researchers are attempting to transfer a gene that enables rye to tolerate aluminum into wheat to produce a new strain that can be grown on aluminum-containing soils where normal wheat will not survive **[45]**. Development of plant varieties for acid soils may promote the use of direct-application phosphate rock under appropriate agroclimatic conditions.

Researchers at Sweden’s University of Lund incorporated a gene that makes a bacterial version of oxygen-transporting hemoglobin into tobacco plants. They were attempting to develop plants that would better survive in environments where oxygen is depleted, such as waterlogged soils. They found instead that the hemoglobin gene produced a variety that exhibited early germination and enormous spurts in growth. The modified plants thrived and outgrew their natural relatives. This team is now testing the gene in primary crops such as rice and maize to see whether they also show these large increases in growth rates **[46]**.

Some of the more spectacular accomplishments of biotechnology were reported in 1996. Teams from Roslin Institute and PPL Therapeutics in Edinburgh, Scotland, revealed they had successfully cloned a sheep **[47]**, and ABS Global, Inc., a cattle-breeding company in the United States, announced that they had cloned a calf **[48]**. Scientists speculate that the combination of genetic engineering and cloning technologies might make it possible to mass produce cattle that furnish milk containing special proteins for medical purposes.

The availability of bioengineered crops and livestock, such as those discussed above, could seriously impact the world’s capacity to produce food. Farmers who see the potential of higher earnings from new high-value specialty crops might well decide to focus efforts on these areas instead of growing food and fiber commodities. Mycogen’s Caulder predicts, «The U.S. farmer is going to be moving away from just large volumes of commodity crops and into specialty crops that have specialized uses on the other end» **[42]**. If Caulder’s vision comes true, the fertilizer industry could see a shift in the types of products it is expected to provide. Farmers who grow high-value specialty crops might be more willing to adopt the methods of precision agriculture. They would want a wider range of fertilizer grades and customized formulations that include secondary nutrients and micronutrients. They might be willing to spend more for controlled release fertilizers that would maximize nutrient use efficiencies. Increased use of fertigation and hydroponics would require that more water-soluble products be available. Introduction of crops that can survive in acidic soils will increase the need for fertilizers that are effective on these soils. The introduction of rapid growth, high-yielding «super crops» could generate large increases in the productivity of small farms. Obviously, much work is needed to develop these plants, and even more research is needed to learn their nutrient requirements and what agricultural practices will be needed to successfully grow them.

Conclusions

Proceedings of IFA Technical Conferences that have been held during the past 50 years show that many advances have been made by the fertilizer industry in developing new products and manufacturing technologies to meet challenges that it has encountered. The future will bring more demands for improvements if the industry is to successfully meet challenges that will develop if existing trends continue. Most analysts agree that production of food and other agricultural products must be increased to supply the needs of a growing world population, and nutrients that are removed by intensified agriculture must be replenished if crop production is to be maintained at high levels.

The worldwide demand for fertilizer products is expected to increase. In many areas fertilizer producers and consumers, who are expected to meet the needs of the world, will be expected to comply with more restrictive environmental standards on the manufacture and use of fertilizers. Eventually, this combination of expectations may require that properties of future fertilizer products be improved to achieve higher nutrient utilization efficiencies and lower losses of nutrients to the atmosphere, ground water, and surface water than can be attained with current products. Improved technologies to produce lower cost, controlled availability products might be required to satisfy future demands for high efficiency, yet environmentally harmless, fertilizers.

Fertilizer producers in the future must also be prepared to cope with shifts in the properties and costs of their raw materials that could occur as existing materials are consumed. They also could face changes in the costs and availabilities of energy sources that would significantly impact production and transportation economics.

It is suggested that highly technical advances and solutions will be most applicable to those countries or regions where an adequate technological and economic base exists to facilitate implementation. In developing-country situations infrastructure, transportation, industrial and economic development, and social conditions may not be conducive to the use of many technological advances and complicated solutions. In these cases, the use and implementation of appropriate technology will be more effective.

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