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Review

Biotechnology in plant nutrient management for agricultural production in the tropics: The research link

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The potential benefits of biotechnology are extraordinary and traverse sectors like agriculture, environment, health, industry, bio-informatics, and human resource development. In agriculture, biotechnology research has helped to improve the understanding of diseases, to improve the diagnosis and treatment of diseases, to improve resistance to herbicides/insects/pests/diseases/drought, to improve crop varieties and yields, marker assisted selection breeding, to develop new uses for agricultural products, to facilitate early maturation and to improve food and feed nutritional value. The uncertainties and risks of biotechnology are yet to be fully understood but its possibilities are yet also to be fully exploited for agricultural production. Research has currently linked plant nutrition to biotechnology through plants modifications to obtain improved photosynthetic system and enhanced nutrient uptake. Due to the corresponding higher physiological efficiency of the improved crops via the biotechnological modifications, plant nutrient management can be adjusted appropriately. These adjustments ultimately lead to other potential benefits in agriculture that include reduced labour and capital inputs, improved environmental protection and strengthened rural economies, which can translate into sustained agricultural production.

Key words: Biotechnology, research, nutrition.

INTRODUCTION

In the face of growing human population and environmental challenges, current farming methods are proving incapable of meeting requirements for sustainable agricultural production, food security, and economic growth. In Africa, farming is the most important economic activity that contributes 33% of the National Gross domestic Product (FAO, 1996; Persley, 2002; Monsanto, 2002).

The available land suitable for agricultural production is declining due to environmental degradation that includes soil erosion and soil exhaustion, hence poor plant nutrition. Pests, weeds and diseases too, have devastating effects on crop yields in Africa causing large losses of farm produce before and after harvest. Worst still is the cost of insecticides and fertilizers that are considerably high for poor farmers who are forced to use them sub-optimally. This result in higher pest damages and lower yields (FAO 2000; Monsanto, 2002).

With increasing population growth, food production must be doubled by the year 2020 if there is to be sufficient food for all. Agriculture must face and meet this challenge (FAO, 2000). This implies that boosting agricultural productivity is of paramount importance to improve people's welfare and standard of living in Africa. To achieve this, scientists and researchers should embrace appropriate technologies and policies to help transform the agricultural system to become more productive and profitable (DANIDA, 2002; FAO, 2002). Examples of such technologies include plant biotechnology. Biotechnology is a broad term for a group of technologies that employ biological systems, living organisms, or parts of these organisms, to make or modify products or processes, to improve plants and animals, or to develop microorganisms for specific applications. But, plant biotechnology in Africa must be considered in the context of Africa's needs for increased food production, poverty alleviation and environmental protection. Increased productivity per unit of land is critical, not only to feed growing populations and ensue competitiveness, but also to protect biodiversity by conserving indigenous forests, wetlands and natural ecosystems (Wambugu, 1999). Appropriate applications of modern plant biotechnology will include:

a. Improving crops yields via breeding for physiologically more active plants that are highly efficient in nutrient utility.
b. Producing better quality and healthier foods via crops with higher protein, vitamins and mineral contents; also plants with modified fats and long lasting vegetables and fruits.
c. Producing disease, pest and insect resistant crops.
d. Producing herbicide tolerant crops.
e. Producing specially adapted plants, draught tolerant crops, and nitrogen fixing crops.
f. Developing plants that produce edible vaccines (Neutraceuticals).
g. Reducing use of toxic chemical pesticides.
h. Encouraging low-tillage production methods and thereby reduce accelerating losses of topsoil and biodiversity caused by farming in poor, marginal lands.

The intensification of agriculture in the favorable agricultural land areas has come at the cost of damage to the environment, with increasing salinity problems in irrigated areas and damage to human health. Urbanization and industrialization has limited prospects of expanding land available for agriculture except by moving into forests and marginal areas. Marginal areas have poor soils and little irrigation and hence prone to drought.

PLANT BIOTECHNOLOGY PRODUCTS

Biotechnology evolved from traditional practices such as conventional breeding and fermentation. Unlike in traditional biotechnology, 'Modern Biotechnology' involves the application of cell modification techniques that overcome natural physiological, reproductive and recombination barriers but which impart desirable traits for food, medicine and other applications.

Modern biotechnology is defined as "any technique that uses living organisms or parts thereof to make or modify products, to improve plants or animals or to develop microorganisms for special use" (FAO, 2002). Plant products of biotechnology have been available in the market for some time now. These modified crops look like their traditional counter parts, but they possess special characteristics that make them superior. These crops benefit both the farmers and consumers. Farmers gain higher crop yield and have increased flexibility in management practices; while consumers have "healthier crops". Plant products of biotechnology approved for food uses have been modified to contain traits (Table 1) such as disease resistance, herbicide tolerance, altered nutritional profiles and enhanced storage. These are termed as the 1st generation genetically modified (GM) crops.

The 2nd generation GM crops are now improved towards producing increased nutritional and or industrial traits, which is very crucial in countries with dietary deficiencies. Some examples include potato with higher starch content, rice enriched with iron and vitamin A, edible vaccines in maize and potatoes, maize varieties that grow in very poor conditions, and healthier oils in soybean and canola, pest tolerance in fruit trees, reduced allergens in peanuts, and protein enrichment in cereals, ripening controlled pineapples (Bongcam and Poirer, 1999) (Table 1).

CURRENT PLANT BIOTECHNOLOGY RESEARCH

Tissue culture

Commonly referred to as "traditional biotechnology", it is the cultivation of plant cells, tissues, or organs on specially formulated nutrient media. This is an important technology that leads to disease free high quality planting materials, rapid production of many planting material, improved growth and yield, uniform planting time and product quality. Unfortunately, tissue culture is labour intensive, time consuming, and can be costly. Important plants in Africa grown in tissue culture are oil palm, banana, eggplant, pineapple, cassava, sweet potato, and tomato (Devries and Toenniessen, 2001). Example of two important breakthroughs have been the tissue culture banana in Kenya (Wambugu and Kiome, 2001) for the production of quality planting materials and the "new rice for Africa" (NERICA) in Guinea, combining the Africa rice (*Oryza glaberrima*) and the Asian rice (*Oryza sativa*) through a backcross embryo-rescue (WARDA, 2005).

Marker assisted selection

A selection tool that reduces breeding time frame, reduces workload and space. The process of developing a new crop variety can take 14 - 25 years. But plant biotechnology via the selection of traits using the MAS can shorten this to 7 - 10 years. This is based on the fact that a plants genetic material that distinguishes one plant from the other is encoded in the DNA. Instead of selection by phenotype, breeders identify specific genes using genetic or molecular markers. The markers are a sequence of nucleic acid, which makes up a segment of DNA. These markers are located near the DNA sequence of the desired gene. The markers and the genes are close together on the same chromosome and tend to stay together as each generation of plants are produced i.e. they are genetically linked. If breeders can find the marker of a gene, it means that the desired gene is present. Using genetic mapping, researchers can analyze only a tiny bit of plant tissue, even from a newly germinated seedling. Several marker systems have been developed and are applied to a range of crop species

Table 1. Plant products of biotechnology.

Improved crop species	Trait characteristic
Herbicide tolerant soybean Herbicide tolerant cotton Herbicide tolerant corn	Has a gene providing resistance to some broad spectrum herbicide.
Insect resistant corn	Bt gene against corn borers
Insect resistant potato	A protein resistant to the potato beetle
Insect resistant cotton	A protein resistant to boll worms and bud worms
Virus resistant potato	Modified to tolerate PLRV* and PVY*
Virus resistant squash	Resistant to the WMV* and the ZYMV*
Virus resistant papaya	Resistant to PRSV*
Delayed ripening tomato	Has extended shelf life
Canola	A modified rapeseed product

*PLRV, Potato leaf roll virus; PVY, Potato virus Y; WMV, Water melon virus; ZYMV, Zucchini yellow mottle virus; PRSV, Papaya ring spot virus.
Modified from the USDA (2001) and Essential Biosafety (2002).

Table 2. Commonly used marker systems.

Feature	RFLPs	RAPDs	AFLPs	SSRs	SNPs
DNA quality	High	High	Moderate	Moderate	High
PCR-based	No	Yes	Yes	Yes	Yes
Ease of use	Not easy	Easy	Easy	Easy	Easy
Number of polymorph loci analyzed	1.0-3.0	1.5-5.0	20-100	1.0-3.0	1.0
DNA required (µg)	10	0.002	0.5-1.0	0.05	0.05

Modified from Korzun (2003).

(Barone, 2003; Grube et al., 2000). These are (Table 2), Restriction fragment length polymorphisms (RFLPs), Random amplification of polymorphic DNA's (RAPDs), Simple sequence repeats (SSRs) or microsatellites, and Single nucleotide polymorphism (SNPs). The molecular markers also allow the creation of new sources of genetic variation by introducing new and desirable traits from wild varieties into elite lines. The main uses of molecular markers are assessment of genetic variation and characterization of germplasm; identification and finger printing of genotypes; estimation of genetic distances between population, inbreeds, and breeding materials, identification of sequences of useful candidate genes and detection of monogenic and quantitative trait loci (QTL) (Table 2).

Herbicide tolerant crops

Lowers input costs in terms of applied nutrients and weeding, encourages the use of environmentally friendly herbicides, less soil erosion therefore enables no-till farming practices, better weed control, improved yields and less crop damage (Carlson et al., 1997). For example, the use of herbicide tolerant soybean lead to reduced fertilizer application, reduced weeding and hence a saving of 216 USD. Adoption of Bt cotton has led to a 5-fold decrease in usage of pesticides in China while it resulted in a reduction of 78,000 tons of formulated pesticide use (James, 2004). Bt cotton in India resulted in yield increase from 308 to 450 kg/ha between 2001 and 2004 (James, 2004).

Virus/insect tolerant crops

Less chemical pesticides used (benefits the crop and the environment), less negative impact on non-target organisms, less chemical residue on product, Lower in put costs, lower fungal toxin levels due to reduced insect damage and "peace of mind" management (Carpenter and Gianesis, 2001). Use of Bt cotton in South Africa under irrigation showed 18% higher yields, reduced spraying to only two and a reduction in fertilizer application by 20% (Van der Walt, 2000). More than 20 genes for resistance to various plant diseases have been isolated (Baker et al., 1997), tagged and mapped using molecular markers in many crops species (Zhang and Yu, 1999).

Diagnostics

Early detection and early treatment of disease causing organisms is critical in effectively controlling disease losses. Visual detection at plant level is usually possible only after major damage to the crop has occurred (Webster, 2000). Modern biotechnology techniques provide more accurate and quicker identification of pathogens using new diagnostics that identify molecular aspects of the pathogen. The diagnosis is based on rapid detection of DNA or proteins that are specific to each pathogen, disease or condition (James, 2000). This can be extended to nutrient deficiencies during the latent periods to allow for timely fertilizer applications.

Drought and salt tolerance

Drought, extreme temperatures and high salinity are major limiting factors for plant growth (Altman, 2003). If plants can be redesigned to better cope with abiotic stress (Zhang et al., 2000) agricultural production can be increased dramatically. Development and utilization of stress-resistant genotypes would be an efficient approach. Plants respond to stress by adjusting their morphology, physiology and biochemistry. Genes regulate these responses; hence efforts are geared towards isolating and characterizing these genes. Among stress-induced genes isolated to date, several major groups of genes have been targeted for improving abiotic resistance in plants. This includes genes encoding enzymes for the biosynthesis of compatible compounds, heat shock enzymes, transcription factors and proteins required for homeostasis. A more promising line of research is the use of gene coding for citrate synthase, the enzyme for biosynthesis of citric acid (Fuente et al., 1997). Transgenic sugar beet plants with an elevated expression of this gene showed an enhanced tolerance to aluminum and an also increased uptake of phosphate in the acidic soils as a result of excretion of citrate.

Biofertilizers and biopesticides

Microbes function as both providers and defenders. They can contribute to plant nutrition by converting important macromolecules into forms usable by plants. In view of the rise in the costs of chemical fertilizers and their adverse effects on the environments, the potential of certain microorganisms to avail nutrients to crops plants as biofertilizers has been recognized (Zafar, 2000). Most biofertilizers fix atmospheric nitrogen to ammonia by complex metabolic process. Two types of biofertilizers are known. The symbiotic, which require association with plants, are represented by *Rhizobium*, and the free-living, which fix nitrogen independently, include the *Azotobacter*, *Azospirillium*, blue green algae and *Azolla.* These biofertilizers are particularly important in tropical countries where soils are deficient in organic matter and essential plant nutrients. Biopesticides as an alternative to chemical pesticides are becoming important in control of pests due to two reasons: They are target-specific and they do not leave harmful residues. Important pesticides include, trichogramma (egg parasitoid) to control lepidoptera pests, fungi (*Trichoderma* and *Gliocladium*) to control root rot and wilt disease in pulses, *Bacillus thuringiensis* and neem. The fungus *Penicillium bilaii* allows plants to absorb phosphates from the soil.

THE RESEARCH LINK: BIOTECHNOLOGY AND PLANT NUTRITION

In many developing countries, soil infertility limits productivity. Plant nutritional research can raise productivity by diagnosis of nutrient deficiencies and toxicities of crops on previously unfertilized soils, their corrections with minimal fertilizer and treatment costs, and development of cultivars with high nutrient efficiency in deficient soils and high tolerance of natural toxicities (Loneragan, 1997).

Advances in plant breeding and agronomy often reinforce each other. Example the dwarf wheat and rice not only reduced the amount of photosynthate needed for straw but also increased the benefit of adding more fertilizer (Brown, 1997). Most breeding programs have confined their research to selecting and breeding cultivars with heightened ability to cope adverse soil conditions. In a few cases, genetic information collected in breeding programs has enabled researchers to relate nutrient efficiency to specific genes. Nutrient efficiency may involve a variety of mechanism in different species and different genotypes of a single species. Example the gene position for copper efficiency in barley and the cDNA clone isolated for manganese efficiency in barley (Graham, 1984).

Different species and different varieties of plants often show marked differences in adaptability to soils low in nutrients. Such differences are due to either:

1. the ability to uptake nutrients from soils of low availability or
2. the ability to utilize nutrients more efficiently in plants

Hence acquiring sufficient understanding of the physiology of nutrients is critical in having an efficient management system.

Yield potential research

Genetic engineering can be used to modify certain physiological processes for higher yields. Gan and Amasino (1995) reported a system conceived to delay leaf senescence by autoregulated production of cytokinin. This was seen observed in transgenic tobacco plants, which showed a significant delay in leaf senescence, and a corresponding large increase in flower number, seeds and biomass. Yield improvement has also involved research in both agronomic nutrient uptake involving the major nitrogen, phosphorous and potassium nutrients, i.e. the enhanced ability of their uptake by plants and enhanced photosynthesis.

Research involving transgenes governing photosynthetic system for higher yields has been reported. Schittenhelm et al. (2002) reported improved yield in potatoes having the phytochrome B oxidase isolated from *Arabidiopsis thaliana*. A high-affinity phosphate transporter gene (PHT1) has been isolated from *A. thaliana*. This gene showed an increase in the rate of phosphate uptake when over expressed in cultured tobacco cells (Mitsukawa et al., 1997). Kato et al. (1997) characterized phenotypically tobacco mutant plants, which over expressed the axi1 gene, under phosphate deficient conditions.

Plant genes encoding transporters for inorganic N have also been isolated and characterized (Wiren et al., 1997). An enhanced nitrite transporter (Nitr1) gene in the chloroplast envelope of the tobacco plant and isolated from the cucumber plant showed an increased utilization of nitrate (Oka et al., 1997). Increased nitrogen assimilation and plant yield can be investigated by over expressing this gene. Potassium uptake system can be affected by over expression of heterogeneous K channels that enhance K absorption (Wei-ming et al., 1997). Currently ongoing research is on the molecular aspects of water and ion transport under salt and drought stress.

Diagnostic techniques research

Plants have complex mechanism to adapt themselves to changes in environmental conditions such as nutrient availability. These mechanisms include the pattern of gene expression. To understand the mechanism, it is useful to isolate and analyze mutants or transgenic crops with altered responses to environmental changes. It is important to be able to predict nutritional disorder in early stages and to take effective counter measures prior to the appearance of visual symptoms (Horiguchi, 1989). Nutrient disorders can be diagnosed by analyzing phenolic compounds (eg. Anthocyanins and organic acids) that show sensitive response to nutrient deficiency (Chisaki and Horiguchi, 1997). Studies for nitrogen, phosphorous and potassium deficiency in rice, barley and field beans show the accumulation of phenolic compounds prior to visual browning symptoms. Some visual symptoms caused by nutrient deficiencies are due to disorders caused by the phenolic compounds and is gene mediated. Selection of nutrient efficient lines in various crops can be done through *in vitro* technology. Nutrient stress can be done on basal medium in the laboratory and selection of plant cells, tissues and mutants thereof selected thereof. Selected lines can then be further characterized for morphological, physiological and yield parameters. This is based on the observation that there is genetic control of plant nutrient uptake. Genes corresponding to induced man-ganese transport in the manganese-stressed tomato roots have been screened, cloned and sequenced by Kitano et al. (1997), which also showed the enhanced activity of Mn uptake in Mn-deficient roots of tomato and screening of Mn-deffciency-inducing genes, cloned by PCR-assisted differential display.

CONCLUSION

Biotechnology is only one tool, but a potentially important one, in the struggle to improve food security and reduce malnutrition. The uncertainties and the risks are yet to be fully understood and the possibilities are yet to be fully exploited. Biotechnology is by no means a panacea, but should be considered as part of a holistic solution towards meeting farmer's needs via sustainable agricultural production. According to FAO (2006), plant biotechnology provides powerful tools for sustainable development of Agriculture as well as the food industry. When appropriately integrated with other technologies for the production of food, agricultural products and services, biotechnology can be a significant assistance in meeting the needs of an expanding and increasingly urbanized population in the next millennium (FAO, 2006).

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