Nutritional Improvement of Horticultural Crops through Plant Breeding

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Improvement of nutritional quality of horticultural crops will be a rewarding activity for plant breeders as we enter the 21st century. In industrialized countries where sufficient food is available to most of the population, there is an increasing realization that nutritious food can play an important role in assuring a healthful life style and that eating is not solely for sustenance and body growth. People are beginning to consume more healthful foods that can alleviate problems related to "diseases of overabundance" and diet-related chronic diseases, such as some types of obesity, heart disease, and certain types of cancer (Steinmetz and Potter, 1996). In contrast with areas where food is abundant, many people in some less-industrialized countries still do not have enough food to meet metabolic requirements for normal body growth and development (Brown and Solomons, 1991).

However, simply providing more food will not completely solve the problem. Even when food is sufficient to meet minimal requirements for protein and caloric intake, micronutrient deficiencies may be widespread, especially in some population subgroups (Brown and Solomons, 1991). For example, iron deficiency not only can affect normal growth, but also may reduce appetite, increase lethargy, slow mental development, reduce attention span, and lower immunity to various diseases (Lozoff et al., 1996). Iron deficiency is especially prevalent in adolescent girls and childbearing women (Kanani, 1994). Diversifying consumption to include nutritious fruits, vegetables, and nuts can greatly enhance the quality of predominantly grain-based diets that otherwise are unable to sustain a person in good health.

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PLANT COMPOUNDS FOR HUMAN NUTRITION AND WELLNESS

Nutrition is defined broadly as the sum of processes by which an animal ingests and utilizes food substances. These substances can be categorized as nutrients or nutriments. *Nutrients* are referred to as substances required for normal human growth and development, with macronutrients being those required in relatively large quantities and micronutrients those required in small or minute amounts. *Nutriments* are defined as substances that nourish or promote growth and that repair the natural wastage of organic life. Recently, the term *nutraceuticals,* described as "... functional foods (or food supplements) that are designed to deliver a specific health benefit" (Dutton, 1996, p. 11) has emerged. In this grouping is a varied group of substances, including chicken soup, magnesium, cranberry juice, folic acid, and numerous others with perceived health benefits (Dutton, 1996). The plant substances important to human nutrition must be clearly identified and described if we intend to breed cultivars with improved nutritional attributes.

IDENTIFYING OPPORTUNITIES AND DEFINING STRATEGIES FOR NUTRITIONAL IMPROVEMENT

The idea of improving nutritional properties of food crops has been mentioned previously (e.g., Munger, 1979; 1988; Quebedeaux and Bliss, 1988; Quebedeaux and Eisa, 1990). Additionally, nutritionally important traits can be altered through hybridization and selection; an example is carrot (*Daucus carota* L.) (Simon, 1988). However, breeding successes such as these may not always have a positive impact on nutritionally deficient populations because of other limiting factors that contribute to the complex nature of the problem. To avoid the frustration of achieving genetic changes only to find that the improved cultivars are irrelevant or ineffective for changing nutritional status, the feasibility of breeding for nutritional improvement as a viable intervention strategy must be carefully determined before it is initiated (Table 1). The value of any improvements should be measured by the change in nutritional status and health of the people consuming food products derived from the altered cultivar.

A MULTIDISCIPLINARY TEAM APPROACH

Often plant breeders are accustomed to working individually, or in a multidisciplinary team, primarily with other biologists. However, the success of a nutritional improvement program will involve dealing with complex human, social, and economic factors as well as researching biological questions. Therefore, a well-integrated, multidisciplinary team should be assembled in the early planning stages, and the opinions of all team members should be considered when setting goals, defining objectives, making critical decisions, and evaluating progress. Sustaining teamwork in a multidisciplinary group often is more difficult than anticipated. To begin with, nutritionists, plant breeders, social scientists, and economists each speak a different professional language. Information, jargon, and scientific knowledge familiar to some may be poorly understood by other team members. Considerable effort will be required just to communicate ideas and opinions effectively. Also, for most researchers, primary professional recognition comes from other members of their discipline; despite assurances to the contrary, in academia team research often is not valued as highly as individual accomplishments. Peers who are asked to evaluate another's achievements may not be able to recognize the value and impact of individual contributions to multidisciplinary research. The roles played by team members may not be reflected fully by the priority of authorship on publications, and the type of research reports most appropriate for the situation may not be compatible with standards of prestigious journals. Thus, a continuing pull often exists away from the team back to the more comfortable surroundings of like-minded researchers.

Without a team effort, researchers are likely to approach nutritional improvement from their own discipline-driven perspective and continue to work in relative isolation. Without ongoing constructive criticism from varied stakeholders, including team members with different perspectives, courses of action are likely to be taken that diminish the probability of success, as measured by improved nutritional status of the consumer. For plant breeding programs that by necessity are long term, even a few poor choices resulting in misdirected research may reduce the likelihood of achieving the objectives in a timely manner, if at all.

SHOULD A BREEDING PROGRAM FOR NUTRITIONAL IMPROVEMENT BE UNDERTAKEN?

Careful assessment of whether to undertake a breeding program for nutritional improvement should include considerations such as: 1) is there a need; 2) what will be the impact on the nutritional status and health of human subjects in the target population; and 3) what is the feasibility of a breeding program? (Table 1). By considering important points within each of these broad questions in more detail, situations can be avoided where the likelihood of success is low, and, for promising opportunities, the most crucial factors for success can be assigned a higher priority. Bouis (1995) identified five comparable "core questions" to be addressed in examining a plant breeding strategy for fighting micronutrient malnutrition.

TARGETING NEEDS OF HUMAN POPULATIONS

The nutritional requirements of human populations are often viewed as being uniform, but usually that is not the case. While different people may have similar general basal requirements for growth and development, wide diversity exists among and within human populations, as well as variability among environments in which they live. This diversity results in great inequities in food acquisition, disparities in consumption, differing nutritional requirements, and, consequently, differences in nutrient status. As individuals develop, large differences in micro- and macronutrient malnutrition often occur even among siblings in the same living unit, and such differences almost certainly exist among larger subgroups and populations from different regions and with different food customs (Brown and Solomons, 1991).

An example of these disparities relates to iron deficiency status. Iron deficiencies are most likely to occur in people that consume diets containing large quantities of plant-derived foods and small amounts of animal products (e.g., Khokar and Pushpanjali, 1994; Wyatt and Triana-Tejas, 1994). While total iron content may be high, bioavailable iron may be insufficient in the plant products. There is little need to breed crops with higher total iron content for populations consuming animal products. Even in plant-based diets, breeding for increased concentration of total iron will be of limited value unless there is a concomitant increase in bioavailable iron. To improve the iron status of the consumer in these populations, efforts to increase bioavailable iron should be directed at crops and products likely to be consumed by children, adolescent girls, and childbearing women, because they have the greatest iron needs and are likely to be the most affected (Brown and Solomons, 1991; Demaeyer and Adiels-Tegman, 1985). Although men in these populations may not consume significantly more available iron than women, they are less likely to be severely iron deficient since their needs are much less (Dallman, 1990).

We should not assume that human nutritional needs are the same across diverse cultures, geographic regions, or even seemingly similar populations. The decision to undertake a breeding program for nutri-

Table 1. Steps in determining the feasibility of breeding for nutritional improvement as an intervention strategy for improving the nutritional status of targeted human populations.

1) Assemble a multidisciplinary team
   Plant breeding; production; postharvest biology; human nutrition; production and marketing economics; sociology; consumer acceptance and use

2) Determine whether a breeding program for nutritional improvement should be undertaken
   - a. Is there a need?
     - i. What is the nutritionally based "health problem" or "health improvement" opportunity?
     - ii. What is the target population or subgroup?
     - iii. Which plant substances should be altered to address the need/opportunity in the specific target group?
   - b. What will be the impact on the nutritional status and health of people in the target population?
     - i. How much dietary diversity and buffering? Is the food crop relatively important in the diet?
     - ii. Will improved varieties be acceptable horticulturally, socially, and economically?
     - iii. Can the intervention strategy based on "nutritionally improved varieties" be delivered reliably and on a continuing basis to the target population?
   - c. Can an effective breeding program be established?
     - i. Are there more attractive and/or cost-effective intervention strategies?
     - ii. Are there biological barriers to genetic improvement?
     - iii. What are the costs and cost/benefits of a breeding program?
     - iv. Should nutrient/nutriment content of horticultural varieties be improved regardless of perceived health impact (e.g., as a marketing incentive)?

3) Implement a breeding strategy for improvement
   - a. Identify natural variation and/or create variability for important traits
   - b. Design breeding and selection methods to improve nutritional traits and to maintain yield and quality
   - c. Test for reliable field performance and absence of deleterious effects on humans and the environment
   - d. Provide cultivars in a cost-effective way and at an affordable price

4) Document nutritional benefits and other benefits to the consumer
   - a. Measure changes in plant compounds that are nutritionally important
   - b. Measure impact on human nutritional status

tional improvement should be based on a proper assessment of individual situations. Consequently, the methods of intervention and the role of breeding-based approaches in improving nutritional quality in a meaningful way also are likely to vary.

PLANT BREEDING AS AN INTERVENTION STRATEGY

Breeders intending to select horticultural crops for improved nutritional quality must first identify the important nutritional problems facing human populations. Next there should be an assessment of whether developing a cultivar-based, horticultural intervention program will contribute meaningfully to solution of the problem. This should include a cost/benefit analysis, how well the improved cultivar will be accepted by growers, handlers, and consumers, and whether socially unacceptable consequences are like to result.

Usually, several alternative intervention approaches are available to address the nutritional deficiencies of a particular population subgroup (Bouis, 1995). Developing more nutritious crop varieties through breeding may or may not be a good alternative when important nutritional, economic, biological, social, and ethical factors are considered. While the substitution of an improved variety of a widely accepted crop is considered to be cost-effective in the long term, the development cost and time for development may be substantial. Unless a single variety is widely adapted and acceptable to a large population, multiple varieties must be developed to achieve a major impact, thus raising the total cost of intervention. In some cases, the introduction of improved varieties must be accompanied by altered production practices, seed distribution, and education of growers and consumers to assure adoption and consumer acceptance. The realized benefits must be greater than the various costs associated with development and implementation if this is to be a successful intervention strategy.

MULTIPLE OPPORTUNITIES EXIST FOR CONTRIBUTIONS THROUGH PLANT BREEDING

Examination of the effects of grain-based diets on iron deficiency provides an illustration of several different intervention strategies for alleviating this problem in affected populations (Table 2). Although total iron (and usually zinc) may be present in relative abundance, the estimated bioavailable iron may be as low as 10% of the recommended daily allowance (RDA) (Benetiz et al., 1994). The reasons for this include low levels of heme-bound iron in plants vs. greater abundance in animal products (Forbes et al., 1989), the presence of substances such as phytates, oxalates, and polyphenols that bind iron in insoluble complexes, and the low intake of iron absorption–enhancing substances such as vitamin C. By identifying the possible reasons for low iron absorption in targeted populations, several intervention strategies can be considered.

Dietary supplementation is often the first type of intervention considered. Although attractive at first glance, supplementation has met with mixed success depending on specific circumstances (e.g., Kanani, 1994). In addition to providing chemical supplements, dietary supplementation can also mean the inclusion of other food crops. For example, the bioavailability of dietary iron can be improved by daily consumption of foods rich in vitamin C (Hunt et al., 1990). The iron bioavailability in a grain-based diet can be improved by daily consumption of fruits and vegetables that are rich in vitamin C (Ballot et al., 1987).

Since iron (and zinc) bioavailability is reduced by compounds such as phytic acid, oxylates, and tannins, another strategy to improve iron is to reduce phytic acid (V. Raboy, 1990) by diversifying with foods other than grain (e.g., by adding fruits and vegetables, that are lower in phytic acid) (Khokhar and Pushpanjali, 1994). A second strategy to reduce phytic acid is to add phytase to the diet (Simons et al., 1990) or to increase the level of endogenous phytase in the dietary components (Pen et al., 1993; Sandberg and Svanberg, 1991). A third approach might be to identify or create mutants in the staple grain crops with reduced levels of phytic acid (V. Raboy, personal communication, 1995). A fourth method of reducing phytic acid is through milling, germination, and fermentation (Svanberg and Sandberg, 1988).

Table 2. Iron deficiencies related to consumption of grain-based diets and possible interventions to alleviate those deficiencies.

1) Situation
  - a. Primary Dietary Components
    - Maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.)—Mexico[z]
    - Wheat (*Triticum aestivum* L.) and pulses—Pakistan[y]
    - Sorghum [*Sorghum bicolor* (L.) *Moench*] or maize and Cowpea [*Vigana unguiculata* (L.) *Walp.*]—West Africa[x]
    - Millets (*Pennisetum* sp.) and Soybean [*Glycine max* (L.) *Merr.*]—Asia
  - b. Additional components
    - Cassava (*Manihot esculenta* L.), potato (*Solanum tuberosum* L.), sweet potato, (*Ipomoea batatas* L.)

2) Consequences
  - Iron (and zinc) malnutrition

3) Population affected
  - Primarily children, adolescent girls, and childbearing women

4) Reasons
  - a. Diets low in heme iron, high in non-heme iron
  - b. Low bioavailability rather than low intake
  - c. Insufficient absorbable iron
  - d. High levels of compounds that bind with iron (phytates, oxalates, polyphenols, etc.)

[z]Wyatt and Triana-Tejas, 1994.
[y]Khokhar and Pushpanjali, 1994.
[x]Galan et al., 1990.

Table 3. Intervention strategies to alleviate dietary iron deficiencies.

1) Supplement diet with elemental iron

2) Increase available iron in the diet
  - a. Iron density in edible parts of food crops
  - b. Amount of readily available iron
  - c. Amount of heme-bound iron from plant sources

3) Reduce levels of iron-complexing compounds in foods
  - a. Identify plant mutants with decreased levels of phytate
  - b. Add exogenous phytase into the diet
  - c. Increase concentration and/or alter type of endogenous phytase
  - d. Reduce phytate by germination, fermentation, physical removal

4) Increase intake of vitamin C in the daily diet
  - a. Expand production, availability, and consumption of vitamin C–rich fruits and vegetables
  - b. Improve stability of vitamin C to postharvest conditions

Table 4. Plant nutriment compounds having favorable effects on alleviating diet-related diseases.

Antioxidants—reduce cancer and coronary diseases
  - a. Flavonols and flavonoids
  - b. Carotenoids and lycopene

Omega-3 polyunsaturated fatty acids—reduce heart disease, rheumatoid arthritis, autoimmune disease, and cancer

Blood platelet inhibitory activity—reduces coronary problems

Folic acid—reduces incidence of neural tube birth defects

A plant breeding approach can be used to alleviate iron deficiency by: 1) selecting for increased total iron and bioavailable iron in staple grain crops and other components of the diet (e.g., leafy vegetables); 2) developing varieties with lower levels of compounds that reduce iron availability, such as phytic acid; 3) breeding crops with higher levels of endogenous phytase that can reduce the phytates at consumption (e.g., Pen et al., 1993), and; 4) developing higher yielding, better-adapted varieties of supplemental crops that contain compounds that improve iron availability, such as crops rich in vitamin C (Table 3).

HORTICULTURAL CROPS AS SOURCES OF NUTRIMENTS

There is increasing evidence that many plant compounds falling in the category of nutriments can alleviate so-called "diseases of over-abundance" and certain diet-related chronic diseases when consumed in appropriate quantities (Steinmetz and Potter, 1996) (Table 4). As with the micronutrients, the need for and the impact of these substances often vary greatly among individuals and population subgroups. In deciding whether to embark on a breeding program to increase these compounds in horticultural crops, a set of questions similar to those stated above for micronutrients should be considered. The results to date suggest that, for at least some important nutriments, adequate genetic variability exists to support expected breeding improvement (Table 5).

IMPLEMENTING A BREEDING STRATEGY FOR CULTIVAR DEVELOPMENT

The biological dimensions of the problem must be considered. This includes a determination as to whether there is sufficient natural genetic variation or whether novel variants must be created, whether analytical methods can discriminate between plants with differing levels of expression of important traits, and whether new technology must be developed. Using this information, a breeding program can be assembled with estimates of cost, time for critical steps to be completed, personnel and facilities required, and criteria used to judge the levels of accomplishment and success.

To address the challenge of raising productivity and improving nutritional quality of food crops, breeders have at their disposal not only classical breeding methods of proven value but also powerful new molecular-based approaches for developing new varieties (e.g., Chappell, 1996) (Table 6). Breeding to improve nutritionally related traits can be approached in a step-wise manner similar to that used for other traits. This might include identification or creation of genetic variability, selection for enhanced levels of important traits using either individual phenotype or family mean values, testing for reliable field performance, and the distribution of new cultivars. In addition to improving amount and availability of desirable nutrients, avoidance of undesirable correlated responses, resulting from genetic or physiological linkages between the trait of interest and other traits deleterious to either plant growth or the consumer, is critically important during selection and prior to cultivar release (Table 7).

SUMMARY

Horticultural plant breeders have an unprecedented opportunity to address human nutritional needs by developing fruit and vegetable cultivars rich in nutrients, nutriments, and nutraceuticals. Because complex factors are often responsible for nutritional deficiencies, care must be taken initially to determine the feasibility of cultivar improvement as an intervention strategy that will result in the actual alleviation of nutritional problems in well-defined, targeted human populations. A multidisciplinary research team is best suited to plan and carry out an improvement program, using classical breeding and molecular-based methods for varietal development as one of several alternative approaches to address specific objectives. For most plants, sufficient genetic variability probably exists, either in germplasm collections or from transgenic genotypes, to produce substantial gain from selection. Social and economic factors may be greater impediments than biological constraints to successfully alleviating nutritional problems through a plant breeding–based strategy.

Table 5. Genetic variation for some nutriment compounds in crop plants that are related to health problems.

1) Cancer
   a. Beta carotene (Vitamin A)—carrot (*Daucus carota* L.)[z], tomato (*Lycopersicon esculentum* L.)[y], sweet potato[x]
   b. Quercetin— onion (*Allium sepa L.*)[v]

2) Coronary diseases
   a. Blood platelet inhibitory activity—onion (*Allium sepa* L.)[u]
   b. Altered fatty acid composition— oilseed crops

3) Birth defects
   Folic acid—table beets (*Beta vulgaris* L.)[t]

[z]Simon, 1988.
[y]Tigchelaar, 1988.
[x]Collins, 1988.
[v]Patil et al., 1995.
[u]Goldman, 1996; Goldman et al., 1995.
[t]Wang and Goldman,1995.

Table 6. Contributions of technology to plant breeding.

1) Existing technology
   a. Standard analytical methods
   b. Conservation and use of plant genetic resources
   c. Mendelian genetics and quantitative inheritance
   d. Statistical procedures and biometrical analyses (e.g., analysis of variance, experimental design, combining ability)
   e. Standard breeding methods (e.g., production of hybrid cultivars, modified pedigree selection, standard backcross breeding, inbred backcross line breeding)

2) Emerging technology
   a. Improved analytical methods [e.g., polymerase chain reaction (PCR), high pressure liquid chromatography (HPLC), protein and oil quantification via infrared spectrophotometry]
   b. Biotechnology (e.g., production of transgenic plants), molecular markers for gene identification and cloning, marker-assisted selection, and genetic resource management)
   c. Bioinformatics

Table 7. Important aspects in breeding horticultural crops.

1) Emphasis on nutritional quality for maximum impact on human nutrition and wellness

2) Identification and selection against compounds with toxic and/or antinutritional effects

3) Improvement of product quality and consumer acceptability

4) Selection for better flavor, texture, and postharvest quality rather than cosmetic appearance

5) Breeding for sustainable production by incorporating traits for higher productivity per unit input and biological pest resistance

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