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Review

Elevating optimal human nutrition to a central goal of plant breeding and production of plant-based foods

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ABSTRACT

High-yielding cereals and other staples have produced adequate calories to ward off starvation for much of the world over several decades. However, deficiencies in certain amino acids, minerals, vitamins and fatty acids in staple crops, and animal diets derived from them, have aggravated the problem of malnutrition and the increasing incidence of certain chronic diseases in nominally well-nourished people (the so-called diseases of civilization). Enhanced global nutrition has great potential to reduce acute and chronic disease, the need for health care, the cost of health care, and to increase educational attainment, economic productivity and the quality of life. However, nutrition is currently not an important driver of most plant breeding efforts, and there are only a few well-known efforts to breed crops that are adapted to the needs of optimal human nutrition. Technological tools are available to greatly enhance the nutritional value of our staple crops. However, enhanced nutrition in major crops might only be achieved if nutritional traits are introduced in tandem with important agronomic yield drivers, such as resistance to emerging pests or diseases, to drought and salinity, to herbicides, parasitic plants, frost or heat. In this way we might circumvent a natural tendency for high yield and low production cost to effectively select against the best human nutrition. Here we discuss the need and means for agriculture, food processing, food transport, sociology, nutrition and medicine to be integrated into new approaches to food production with optimal human nutrition as a principle goal.

Contents

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1. Introduction

An obvious but rarely stated goal of food production is to provide the human species with the proper nutritional factors to allow each person to reach their full intellectual and physical potential. However, in practice the two most important drivers of food production are optimal yield and minimal cost. The goals predicted for agriculture in the future forecast more of the same; i.e. that plant production will target supplying adequate calories for an ever increasing population, while also addressing the growing concern about the impact of agricultural practices on the environment [1], but not the need for superior nutritive value to enhance human health.

There has been increasing interest over the past several decades in improving the nutritional quality of crops. The wide-scale release of lines of quality protein maize (QPM) now being cultivated in Africa, Asia and Latin America [2] is one of the fruits of concerted efforts of breeders to improve nutritional quality of crops. The upcoming releases of biofortified crop varieties planned by programs such as HarvestPlus (http://www.harvestplus.org) and AgroSalud (http://www.agrosalud.org/) also illustrate the increasing interest in enhancing nutritional quality of crops. Nevertheless, enhancement of nutritional value of crops is high on the list of goals or accomplishments of rather few plant breeders, even though improved nutritional value is of critical importance for human well-being. In a hungry world, where the rate of increase of food availability trails behind the rate of increase of the demand for food, it is unlikely that enhanced nutritional value of crops can be a goal in itself. This will be particularly true when goals for enhanced nutritional value are for single nutrient traits rather than overall nutritional quality of crops. In this paper, we propose fundamental changes in current strategies of plant breeding, crop production, and food and feed processing to better facilitate the goal of production of more highly nutritious plants and plant-derived foods.

To develop commercial varieties of crops with enhanced nutrition, it may be essential to link nutrition to a commercial driver such as yield. In the case of crop lines biofortified for mineral nutrients, yield increases can go hand in hand with nutritional quality [3]. Unfortunately and inadvertently, high yield, pest resistance and low cost can also select against the best human nutrition, which we have called "The Breeder's Dilemma" [4]. In this paper we will point out more examples of this conflict and describe their origins. The exciting challenge for the future is to adjust research priorities in the way plant selection and plant breeding are accomplished to overcome this conflict. The ultimate goal is to create a sustainable food production system that meets the needs of the global population in terms of calories and concomitantly addresses important needs for balanced amino acids, balanced essential fatty acids, optimal trace and macro-minerals, and vitamins, with foods low in toxins or anti-nutrients. The food production methods will need to account for the potential conflicts between optimal nutritional quality for humans and agricultural animals and the physiological needs of plants for growth and defense against pests and disease.

2. Evolutionary context of plants as food

Cereal grains are archetypical of the role of staple crops in the diet of modern humans and the effort invested in their breeding. Three cereal grains: wheat, maize (corn), and rice, constitute 75% of the world's total caloric intake. Over 50% of all the protein consumed by humans world-wide is low nutritional quality protein provided by wheat, maize, rice, barley, sorghum, oats, rye and millet [5]. From an evolutionary perspective, our modern reliance on grains is a dramatic shift away from the diet to which humans have evolved. Earlier than 15,000–100,000 years ago, *Homo sapiens* survived via hunting, fishing, and foraging. After about 10,000–15,000 years ago, during what might be considered as possibly the first 'agricultural revolution', a confluent series of factors contributed to domestication of plants including cereal grains as sources of food. The advantage of such grains was that they could be stored over several years, thereby being a reliable source of food during unfavorable conditions.

Some ethnological and archeological studies suggest that almost immediately after transition to grain-based diets, humans experienced reductions in stature, increases in infant mortality, a shrinkage of life spans, increases in infectious diseases and multiple nutritional deficiencies, including iron deficiency anemia and mineral disorders impacting both bones and teeth [5–7]. It has been argued that widely differing assumptions about different preagricultural regimens have little impact on the estimated dietary essential omega-6/omega-3 fatty acid ratios, for example, which have major health impacts as discussed later [8]. We should note that there are other detailed ongoing studies of the Neolithic demographic transitions of instances where human populations rose 200-fold in a short period of time illustrating the disagreement about aspects of the Paleolithic diet [9]. However, it is well accepted that our foods have changed at a considerably greater rate than our inherent physiology and the underlying genes, which have changed rather minimally in the last 10,000 years [10,11] and essentially not at all in the past 40–100 years [12]. Modern progress in hygiene and developments in medicine have led to reduced infant mortality and longer average life spans, especially where cereal grain-based diets could be supplemented with other sources of nutrients. Nonetheless, many of the negative consequences of the transition to grain-based diets remain with us today. The inadequacies of high-carbohydrate and grain-based diets have been summarized at length [5,7,13]. Furthermore, over the last 200 years, as the population has become more urban, there has been a striking separation of food production from food consumption. Transportation of food away from its source of production has amplified the roles of marketing, intermediary distribution, and processing; and shelf life considerations have influenced the choice of varieties grown, thereby leading to reduced importance of traditional local foods.

The inadequacy of cereal grains as a primary food for humans arises from the fundamentals of plant physiology. Plant seeds are packed with compounds stored as sources of energy for supporting germination. Their carbohydrate, protein and lipid profiles reflect the specific requirements for seed and seedling survival. This nutrient profile, especially after selection during domestication [14], is far from optimal for human or animal nutrition. For example, the seeds of most cultivated plants contain much higher concentrations of omega-6 fatty acids than omega-3 fatty acids than is desirable for human nutrition [15,16], with few exceptions such as flax, camelina (*Camelina sativa*) and walnuts. Temperature is an important regulator of the ratios of the unsaturated fatty acids in plants, with growth at colder temperatures in temperate climates favoring the production of the omega-3 fatty acids in seed oils and moderate to warm temperatures favoring expression of the omega-6 and saturated fatty acids [17–19]. Seed germination during cold temperatures requires higher concentrations of polyunsaturated triglycerides that are in liquid form even at sub-freezing temperatures. Cold tolerant crops such as camelina and flax contain seed oils that are high in omega-3 oils, possibly enabling germination in cold soils. However, the major oil crops, such as corn, soy, sunflower, safflower, and canola are warm- and hot-season crops that are high in omega-6 oils. High dietary intake of omega-6 oils impedes the desaturation and elongation of the omega-3 oils to produce the long-chain omega-3 fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)