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Grain Amaranth

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INTRODUCTION

This paper provides a current overview on grain amaranth with an emphasis on currently available information about the utilization of germplasm to promote more efficient production of the crop. Additional aspects about grain amaranth can be found in two previously published monographs, each of which include extensive bibliographies (National Academy of Sciences 1984; Feine et al. 1979).

At Rodale Research Center (RRC), we view new crops as important resources for improving the health and vitality of agriculture. The selection of appropriate genetic resources can reduce the need for purchased inputs. Each new crop under development at RRC has valuable characteristics, such as drought tolerance, the ability to reduce soil erosion, or the ability to fix nitrogen. The goal of new crops research at RRC is to utilize new crops to enhance the natural resource base, and to maximize the profitability of cropping systems.

Since 1976, work has been in progress at RRC to expand the production and utilization of grain amaranth, a crop which has unique nutritional and agronomic attributes. The primary objective of the RRC amaranth program is the development, characterization, and utilization of grain amaranth germplasm. A germplasm collection with 1400 accessions from all the major grain amaranth growing regions of the world has been assembled at RRC.

One motivating factor for the initiation of the amaranth research evolves from the perceived need to broaden the food base by the utilization of underdeveloped food materials (National Academy of Sciences 1975). As work has progressed, we continue to find reasons for promoting the crop, although it must be stated that grain amaranth is not a wonder crop.

Farmers face the same soil conservation challenges when they grow amaranth as when they grow any other annual row crop. However, amaranth does appear to have special uses in some areas where farmers have limited options, especially in those areas with limited rainfall. The drought tolerant characteristics of amaranth make it a prospective dryland crop for farmers in semi-arid areas. In irrigated areas, amaranth provides an alternative for farmers who seek to reduce irrigation costs, as well as to reduce the potential for sod salinization (Weber et al. 1988).

The many amaranth food products which are now available on the market in the USA, make an important contribution to promoting the concept of diversity in food and agriculture.

HISTORY AND TRADITIONAL USES

The grain amaranths (*Amaranthus* spp.) are native to the New World. Pre-Columbian civilizations grew thousands of hectares of this pseudo-cereal. Some indigenous populations are said to have used grain amaranth, along with maize and beans, as an integral part of their cropping schemes. The Aztecs relied on amaranth seeds (or "grain") as an important staple (National Academy of Sciences 1984).

The reasons for the decline of amaranth after the arrival of the Spanish are unclear. In an effort to explain the decrease in grain amaranth cultivation, fanciful myths have arisen. The mystery is especially intriguing when one considers that maize, with which amaranth co-evolved, was selected and developed into a major world crop. The small seed size of amaranth may have been a partial cause for the reduction in amaranth cultivation. A small seeded crop, such as amaranth, requires greater attention to detail in the early parts of the growing season than does a larger seeded crop, such as maize.

By the middle of this century, the cultivation of grain amaranth had declined to the point where it was grown only in small plots in Mexico, the Andean highlands, and in the Himalayan foothills of India and Nepal. Even now, there is evidence that some traditional farmers are abandoning the cultivation of local landraces of amaranth as they devote more of their land to high-yielding "modern" crops.

The word "amaranth" in Greek means "everlasting" And in fact, the crop has endured. To assure a small annual supply for this specialty crop, traditional farmers have continued to grow small plots of the grain each year. Furthermore, the distinctly beautiful appearance of amaranth has helped to prevent the crop from slipping into obscurity. The enchanting beauty of the vividly colored leaves, stems and seedheads in an amaranth field is a sight which evokes emotions that other crops cannot stir.

MODERN PROSPECTS

The cultivation of grain amaranth is now in the process of expanding in a number of countries. Over the past 15 years, there have been some well-executed projects in which researchers, farmers and food processors have invested imagination, time and money on this crop. Grain amaranth research at RRC focuses on three areas: germplasm preservation and utilization, the development of improved lines, and outreach and information dispersal. Partial funding for our projects has been provided by the United States Agency for International Development (USAID) and the Jessie Smith Noyes Foundation.

Over the past ten years, RRC has sent seed of segregating accessions and improved lines of grain amaranth to researchers in over 70 countries. Many of those countries now have internally-funded amaranth projects of their own. We are aware of active amaranth research and production projects in Venezuela (Gouveia 1986)

China (Sun et al. 1987), and a USAID sponsored amaranth research project in Nigeria (Capstone 1987). Grain amaranth research has been served well by a six-year grants program that was administered by the Board on Science and Technology for International Development (BOSTID) of the National Academy of Sciences (NAS). The BOSTID program has provided funding for research on nine projects in five countries (Mexico, Guatemala, Peru, Kenya and Thailand). Annual meetings of the grantees have allowed for an exchange of information on: the progress on germplasm evaluation, cultural methods, food processing, and nutrition. In addition, BOSTID has funded a quarterly scientific newsletter, published in Guatemala (Amaranth Newsletter, c/o Dr. Ricardo Bressani, Instituto de Nutricion de Centroamerica y Panama, Apartado Postal 1188, Guatemala, GUATEMALA). A summary publication of the research findings at each research location is currently being assembled.

There has been increasing interest in grain amaranth in the international community. A number of conferences for the promotion of the crop have been held in 1977, 1979 and 1984 (Rodale Press, Inc. 1977; Rodale Press, Inc. 1980; Rodale Press, Inc. 1986). Conferences were hosted in Mexico in 1984 and 1986, with presentation of papers from individuals representing 19 different Mexican institutions. The range of subjects covered included ethnobotany, germplasm development, agronomic research, nutrition and processing (Memoria del Primer Seminario del Amaranto 1984, Memoria del Colloquio Nacional del Amaranto 1987). In 1987, an annual amaranth conference was initiated in the People's Republic of China to bring together researchers in over 22 provinces (Sun 1987). Also in 1987, The University of La Pampa in Argentina hosted a national conference on amaranth, with papers presented by 17 researchers (Actas de las Primeras jornadas Nacionales Sobre Amarantos 1987).

The Rodale Research Center is currently in contact with researchers at 29 institutions in the USA and Canada (supported by federal agencies, state universities and private institutions) who are conducting applied research on various aspects of grain amaranth development—including genetics, plant breeding, agronomic studies, forage utilization, and nutritional value of the grain. The Canadian government has sponsored yield evaluations at three sites.

The American Amaranth Institute (AAI), which has been organized to help promote research and development, is working closely with many of the research institutions. The AAI is also working with Crop Improvement Associations to develop standards for amaranth seed certification.

The synergism of the completed and on-going projects at RRC, the domestic and international institutions, and the AAI has provided a wealth of information and experiences for modern farmers to draw on as they initiate commercial production. Farmers are developing innovative techniques to find ways to produce grain amaranth economically. As a result of their ingenuity, the supply of commercially available amaranth has increased to the point where several food companies are producing amaranth products which can be purchased in many stores in the USA. The rising demand for amaranth food products will require a substantial increase in amaranth production during the coming years. In 1988, approximately 1200 ha of grain amaranth were planted in the Great Plains of the USA, and 1000 ha were planted in the Sacred Valley of the Incas in Peru. In addition, we have received reports from collaborating researchers that there are substantial plantings of grain amaranth in Mexico, Kenya, and China to produce grain for export, as well as for internal use.

Those of us who have worked on the crop for many years are pleased to see the advancements that are being made in the development of this crop. However, it is important to stress that many research questions and developmental opportunities still exist for those who wish to make an impact on the expansion of this crop.

GERMPLASM

The genus *Amaranthus* includes approximately 60 species (National Academy of Sciences 1984), most of which are widely dispersed weeds. The weedy amaranths are referred to as "opportunists" (Sauer 1955) because of the fact that they thrive in disturbed soils and tend to be associated with agricultural practices. The tradition of using some species of feral amaranths as a forage for livestock, as greens for human consumption, and as dye plants (Fig. 1), continues in many places.

Although this paper is focused only on grain amaranth, it must be noted that the leaves of many cultivated species of *Amaranthus* are commonly eaten as a "potherb" or leafy vegetable throughout the world (National Academy of Sciences 1975). There is no clear dividing line between a "grain" type and a "vegetable" type. The leaves of amaranth plants which are being grown specifically for grain can serve as a food source, if the leaves are consumed when the plants are young. A few species which are grown primarily in the hot, humid tropics are prized for their high quality leaves. There are many cultivars of the species *A. tricolor* L. which are widely dispersed and cultivated throughout Asia and the South Pacific. The leaves of *A. dubius* Mart. ex Thellung are considered to be a delicacy in many areas of the Caribbean (Martin and Telek 1979). A dark-seeded strain of *A. cruentus* L. is commonly cultivated as a vegetable in West Africa (Grubben 1976).

Amaranth which produce a large amount of biomass in a short period of time, can be used as a forage crop for domesticated animals. In China, amaranth has been cultivated expressly for use as a forage for cattle. There are several cuttings made per growing season. In Peru, the stover is grazed or milled for use as a feed supplement after the seedheads have been hand-harvested. Some types of amaranth accumulate toxic levels of oxalate and nitrate when grown under conditions of stress (Saunders and Becker 1984). Additional research is needed to better define the feeding value, potential toxicity problems and the most appropriate type of amaranth for use as a forage (Weber et al. 1988).

There are three species of the genus *Amaranthus* which produce large seedheads of edible, light-colored seeds (Fig. 2). *A. cruentus* L. and *A. hypochondriacus* L. are native to Mexico and Guatemala. *A. caudatus* L. is native to the Andean regions of Ecuador, Peru, and Bolivia (Sauer 1967). Cultivated land races of the three species have a wide degree of genetic diversity which can be utilized to develop selections of improved lines with suitable characteristics for modem grain production.

Amaranth germplasm is catalogued and stored in germplasm banks in 11 countries (Toll and van Slotten 1982). A descriptive taxonomic key for all the cultivated species of the genus *Amaranthus* was developed by Feine-Dudley (Grubben and van Slotten 1981). Since 1977, RRC has maintained a working germplasm collection. The 1400 accessions in the amaranth germplasm collection include representatives from 12 amaranth species. The collection includes germplasm from banks in other countries, material from germplasm collection trips which were made by RRC staff members, and materials which have been donated by collaborating researchers. The germplasm is catalogued according to "grain type". The grain type categories may actually be a regrouping of the germplasm according to landrace. The grain type categories have proven to be useful to manage the huge amount of variability that exists within each species. Descriptions of all species and the grain types can be found in the RRC germplasm catalogue (Kauffman and Reider 1986).

A majority of the accessions in the RRC germplasm collection were collected as mass selections or single plant selections of cultivated landraces of those species which are commonly grown for their light colored seed. Many selections have been made from the segregating accessions in an effort to create uniform lines. Seed from the amaranth accessions has been distributed to thousands of researchers and farmers around the world. The germplasm collection is the backbone of our varietal improvement program which is aimed at developing agronomically acceptable lines using classical plant breeding and selection methods.

Germplasm characterization is being conducted at a number of locations around the world. Extensive, well-documented amaranth germplasm characterization has been conducted by organizations in India, Peru and Mexico Ooshi 1981, Sumar et al. 1983, Espitia 1986). The USDA Plant Introduction Center at Ames, Iowa has been working to characterize the germplasm and to determine the amount of outcrossing that has occurred. Germplasm from their collection will be entered into the Plant Introduction System for distribution.

Since 1982, the staff at RRC has collaborated with researchers who are conducting observations on 14 selected grain amaranth accessions (representing grain types from the species *A. hypochondriacus L., A. cruentus* L., *A. caudatus* L., and *A. hybridus* L.) to collect information on their performance at distinctly different climates and latitudes (Bressani et al. 1987a, Senthong 1986, Gupta 1986, Duriyaprapan 1986, Espitia 1986). Information generated at each location serves as a starting point to help determine which sources of germplasm should be exploited to develop improved lines of grain amaranth for any given area. Similar observations have also been made to characterize germplasm which was collected throughout India (Joshi 1986). Populations of landraces which were collected from Mexico to Argentina have been observed for their genetic structure (Hauptli and Jain, 1984).

Germplasm enhancement has been conducted at RRC since 1977 using recurrent single plant selection and mass selection. Selections continue to be made for the development of ideotypes which meet the needs of modern agriculture.

In our genetic improvement program we have selected a number of traits which have been relatively easy to isolate, including:

- Reduced plant stature (1.0 to 1.5 m)
- Flowering above the leaf canopy
- Lack of branching
- White or gold seed

- 100 to 120 day maturity
- Higher yield as a result of traits such as a large flower head with a high ratio of pistillate flowers that set seed.

However, a number of other traits still need to be improved:

- Seed size
- Tolerance to insects and diseases
- Seedling vigor
- Reduced shattering
- Standability (resistance to lodging)
- Synchronous drydown of the plant and seedhead
- Ability to be easily threshed
- High protein content
- Functional attributes of the grain

The first released line of amaranth named 'MT-3' was announced by the Montana Agricultural Experiment Station (Cramer 1988). It was selected from a segregating accession of *A. cruentus* L. originally collected in Mexico. Similar programs are presently in progress in Mexico and Kenya. The University of Cuzco in Peru has released three cultivars of *A. caudatus* L. which have been named 'Oscar Blanco, 'Noel Vietmeyer' and 'Alan Garcia'. These three cultivars are being grown commercially on hundreds of hectares by farmers in Peru (Sumar K., L. personal communication, 1988). A cultivar of *A. hypochondriacus* L., named `Annapurna' has been released in India (Joshi 1985).

The first released cultivars have helped to promote the commercialization of this crop. However, the gene pools of all of the cultivated amaranth landraces lack one or more desirable traits which are perceived as requirements for commercial production. For example, with adequate moisture and fertility, all of the improved varieties which mature and produce good seed yields of light-colored grain at northern latitudes reach a height of 2.5 m at maturity, too tall to harvest with modern grain combines.

GENETICS AND PLANT BREEDING

The genus *Amaranthus* provides fascinating material for geneticists to tackle. Amaranth is a predominantly self-pollinated crop, with varying amounts of outcrossing (Hauptli and Jain 1985). By growing amaranth in isolation, it is possible to control the amount of outcrossing for the development of true-to-type lines from segregating accessions within only a few generations of selection.

Basic genetic studies were initiated in the late 1950s. Chromosome counts were made (Grant 1959; Pal 1964). Polyploids were also identified (Khoshoo and Pal 1972). Studies have been conducted to document the amount of variation within Indian populations of amaranth (Vaidya 1984). The possibilities for interspecific hybridization have been documented (Pal and Khoshoo 1973).

The cultivated species of grain amaranth are monoecious. The basic techniques for making emasculations and pollinations have been described (Murray 1938) and refined (Kauffman 1981).

For the past 15 years, Dr. Subodh Jain has led an active program to identify genetic traits for the improvement of grain amaranth at the University of California-Davis (Jain et al. 1986). Efforts have been made to determine the efficacy of different breeding strategies (Kulakow and Jain 1987, Ayiecho 1986). Additional techniques have been studied to determine how to manipulate plant height and increase grain yields (Vaidya and Jain 1987).

The potential for the development of hybrids has been advanced by the identification of gene markers in the program at Davis, and other locations. Plant and seed pigment patterns, leaf characteristics, time of flowering, and determinate vs. indeterminate growth, have been identified (Kulakow et al. 1985, Kulakow and Jain 1985 Kulakow 1987). An additional marker that has been observed in breeding trials at RRC is bract length. The perisperm and starch of the grain can be used as potential gene markers (Okuno and Sakaguchi 1982).

Markers can be used to identify and discard self-pollinated plants in the F1 generation. In addition, markers allow breeders of grain amaranth to avoid the process of emasculation when making crosses. The identification of three sources of cytoplasmic male sterility paves the way for additional hybridization techniques (Peters and Jain 1985, Peters and Jain 1987, Gudu and Gupta 1988).

Genetic investigations have been conducted in India to learn more about the traits which control yield, including harvest index, yield per plant and weight per 1000 seeds (Pandey 1984).

There have also been some unique investigations to identify the mode of inheritance of traits that affect the nutritional characteristics of the grain. Work in Japan has focused on the identification of factors related to the unique starch characteristics of the grain. (Okuno 1985, Konishi et al. 1985). In India, the mode of inheritance of grain protein percentages has been studied (Pandey and Pal 1985).

In 1978, an applied amaranth breeding program was initiated at RRC to develop improved plant types for mechanized production in the USA and Canada. Using classical plant breeding techniques, we have developed a series of advanced breeding lines (F6-generation, and higher) which are being grown at experiment stations and on commercial farms in the USA. The lines are being distributed as part of the "K-series."

One of the lines, `K-343', is the progeny of a cross of a white seeded *A. hypochondriacus* L. from Mexico and a black seeded *A. hybridus* L. from Pakistan. This single line was grown on most of the commercial plantings of grain amaranth in the Great Plains of the USA in 1988. It has an unbranched short plant habit at high plant densities, and slightly earlier maturity, as compared to `MT-3' and other selected Mexican landraces which have been grown by farmers.

The current concentration on one source of germplasm has the potential to provide a serious setback to the development of the crop. Additional resources are needed to initiate and expand applied breeding programs to meet the needs of the anticipated expansion in grain amaranth production. The initiation of the seed certification process which was begun in 1988, will help to address the need for sources of quality seed of improved lines of grain amaranth.

The future of amaranth is dependent on the careful recombinant selection of genotypes from the germplasm collections. We have had to use unusual sources of germplasm to find traits such as early maturity and shorter plant stature. The ideotype required for mechanized production in the USA has a number of characteristics in common with the landraces from Mexico. We have used highly branched sources of dark-seeded *A. cruentus* accessions ("African" grain type) from West Africa as a source for early maturity. A source for short plant stature was found among a few highly branched, shattering, dark-seeded *A. hybridus* L. ("Prima" grain type) accessions from Asia (Fig. 3).

In addition, some traits are affected by environmental influence, such as plant height, days to maturity, plant architecture, and drydown. For example, accessions of *A. hypochondriacus* L., the Nepal grain type, when grown in Kenya (at the equator and in a semi-arid environment), produces short plants (<1 m), with multiple flowering stems, and matures in 60 days with a high harvest index. When the same accession is grown in Pennsylvania, the plants develop a tall plant (>2 m) with a single stem, matures in >160 days and has a low harvest index.

Additional research needs to be conducted to develop information on the barriers that prevent interspecific hybridization. In general, there seem to be few barriers that exist between crosses of *A. cruentus L., A. hypochondriacus,* L. and *A. hybridus* L. However, crosses with *A. caudatus* L. and any of the above species often result in non-viable progeny (Pal and Khoshoo 1972).

We have noted that some grain types within the species *A. hypochondriacus* L., when crossed by *A. caudatus* L. behave differently from others. For example, we have obtained viable F1 progeny from a cross of *A. caudatus* L. by accessions from the grain types "Aztec" and "Nepal" of the species*, A. hypochondriacus* L. However, crosses of *A. caudatus* L. by accessions of the grain type "mercado" of the species *A. hypochondriacus* L., have produced very few viable F_1 progeny. (Descriptions of grain types are listed in Kauffman and Reider 1986.)

To assist in the development of selected progeny from breeding programs, RRC has distributed segregating material from F_2 and F_3 generations of our breeding progeny. The segregating material is grown at the location where the advanced lines will be grown to allow for selection pressure at that location. This technique is currently in progress in Peru, Thailand, China and Kenya, where new progeny are being selected.

To date, the most inclusive evaluations of segregating progeny of interspecific crosses have been conducted in Peru. Most of the first progeny of interspecific crosses observed in Peru did not perform well. However, a few accessions of *A. caudatus* L. crossed with two accessions of the Aztec grain type of *A. hypochondriacus* L. produced progeny that included segregates which were shorter and earlier maturing than the commonly available varieties of *A. caudatus* L. that are presently being grown in Peru. The performance of the segregating progeny and the selections that have been made will provide important clues to help select the most appropriate sources of genetic material to use in future breeding programs in Peru. Similar approaches will be useful at other locations.

Amaranth stands to benefit from some of the new techniques which are being developed in molecular generics. Callus formation has been documented (Flores et al. 1982) which will allow in-vitro cultivation for advancement of breeding lines. The gene expression of certain carboxylases is also undergoing continuing studies (Berry et al. 1986). A project has been initiated in Mexico by Herrers in which gene expression is investigated (personal communication 1987).

AGRONOMIC RESEARCH AND DEVELOPMENT

The most up-to-date summary of agronomic practices for the cultivation of grain amaranth in North America is provided in the annually revised Amaranth Grain Production Guide (Weber et al. 1988). The 1988 edition marked a special milestone, as it was co-produced by the AAI with researchers from the University of Minnesota, the University of Nebraska, and Iowa State University

Beginning in 1979, work was initiated at RRC to develop methods for cultivating grain amaranth with standard farm machinery Precision seeding methods were used to plant 0.5 kg/ha of seed to attain a desired plant density of 300,000 plants/ha (Wagoner 1983). It is possible to harvest the crop using a grain combine after a killing frost, which serves to adequately dry down the plants.

Farmers in the Mid-west and Great Plains (Fig. 4) who began to grow amaranth commercially in the early 1980s needed only to make modifications to their farm equipment to minimize their initial investment. By increasing the seeding rate, they were able to plant amaranth with only minor modifications to existing equipment.

The small seeds of grain amaranth have presented a special challenge in producing the desired plant stand. It is critical that the seed be planted in finely prepared soil, shallowly planted, and packed to assure good seed-to-soil contact. A planting depth of more than 1 cm delayed and decreased emergence (Webb 1985), although in dryland areas, a planting depth of more than 1 cm may be necessary to obtain adequate moisture for germination. A seeding depth of 2.5 cm may be practical in friable soils if seeding rates are adjusted to compensate for reduced emergence associated with increased depth (Webb et al. 1987).

Soil temperatures also play a critical role in seedling emergence. Amaranth is a C4 plant that germinates quickly when sod temperatures reach 15°C to 18°C. Seedling rate should be increased to compensate for lower emergence rates when soil temperatures are less than 15°C (Webb et al. 1987).

No-till methods have been attempted in Minnesota to minimize damage to seedlings from blowing soil particles (Robinson 1986). Amaranth was planted in oat and alfalfa stubble killed with glyphosate prior to planting. Emergence was slower than in conventionally tilled soil, possibly because of lower soil temperatures.

Farmers grow amaranth as a row crop to allow weed control by cultivation. A few growers have grown amaranth successfully in a 25 cm row spacing. However, weeds can become a serious problem with narrow row spacing, if soil surface moisture promotes weed germination at the time of planting. At present, all available post emergence broad-leaf herbicides are phytotoxic to the crop.

There is only limited and preliminary information available on the fertility requirements of amaranth. In a study in Arkansas, one line of *A. cruentus* L. and one line of *A. hypochondriacus* L., were grown at three N rates (0, 100, and 200 kg/ha). A two-fold yield increase was reported at the N rate of 100 kg/ha. No yield advantage was noted at the higher N rate. In a second year, there was no response to N (Endres 1986).

In the first year of an ongoing Minnesota study, a yield response was obtained in *A. cruentus* L. RRC 1011 when increasing amounts of N were applied at rates up to 90 kg/ha; yields were reduced at higher rates. Lodging became a problem at 55 kg/ha and became more severe as the rate of N increased. There was no yield response to added P and K, which was probably due to the high residual levels of P and K in the soil (D. Putnam, University of Minnesota, pers. commun.). Additional research is needed to better define the nutrient needs for growing grain amaranth.

Little is known about actual water requirements of grain amaranth. Observations in many test plots and farmers' fields suggest that grain amaranth is drought tolerant at later stages of growth. Residual soil moisture is needed to assure that emergence occurs. Researchers in China have reported that the water requirement for growing grain amaranth is 42-47% that of wheat, 51-62% that of maize and 79% that of cotton (Yue and Sun, Institute of Crop Breeding and Cultivation, Beijing, China, pers. commun.). Kenyan farmers in regions with marginal rainfall plant amaranth rather than maize because they believe there is less risk of a crop failure with amaranth (Gupta, V.K., University of Nairobi, Nairobi, Kenya, pers. commun.). Observations indicate that amaranth in the coastal desert of Peru requires half the irrigation required by corn (Sumar K., University of San Antonio de Abad, Cusco, Peru, personal communications).

To date, insect and disease problems of economic importance have been minimal. The tarnished plant bug (*Lygus lineolaris*, Palisot de Beauvois) has reduced yields in some years by feeding on immature seed. Research at the USDA Plant Introduction Center in Ames, Iowa is underway to determine the economic threshold of damage, and screen germplasm for lower levels of feeding damage. Work is also in progress to determine the life cycle of the amaranth weevil (*Conotrachelus seniculus* Leconte) which has been found at low levels in commercial amaranth fields (Wilson 1986).

Yields of grain amaranth are highly variable and depend on many factors. Weather patterns play a particularly important role in achieving a good plant stand to maximize yield. A fall weather pattern consisting of a light frost followed by a period of mild weather can account for significant yield losses due to shattering. In some regions, a light frost partially dries the head but fails to penetrate the crop canopy and dry the entire plant sufficiently to permit harvest. Recovered yields in farmers' fields have ranged from 100 kg/ha to as high as 1500 kg/ha. Hand harvested yields have been as high as 4000 kg/ha in Montana (Cramer 1988) and 6000 kg/ha in Peru (Sumar et al. 1986).

NUTRITION AND FOOD USE

The food value of grain amaranth was recognized by people from Mexico to Peru to Nepal long before any, nutritional analyses had been conducted. Because it is easy to digest, amaranth is traditionally given to those who are recovering from an illness or a fasting period. In Mexico, grain amaranth is popped and mixed with a sugar solution to make a confection called "alegria" (happiness). A traditional Mexican drink called "atole" is made from milled and roasted amaranth seed.

In India, *A. hypochondriacus* L. is known as "rajgeera" (the King's grain) and is often popped to be used in confections called "laddoos," which are very similar to Mexican "alegria" In Nepal, amaranth seeds are eaten as a gruel called "sattoo" or milled into a flour to make chappatis (Singhal and Kulkami 1988).

During the last ten years, a number of overviews have been published which provide a wide range of information on the nutritional components, digestibility and potential problems that will be encountered by those who intend to use grain amaranth as a food product (Becker et al. 1981, Teutonics and Knorr 1985, Bressani et al. 1987a, Saunders and Becker 1984, Pedersen et al. 1987). There are several hundred other literature citations that will be included in a bibliographic summary to be entitled "Human Nutritional and Food Applications of Grain Amaranth".

The most studied nutritional aspect concerning the food value of grain amaranth is the identification of the limiting amino acids of the protein component. The crude protein content of selected light-seeded grain amaranths has been reported to range from 12.5 to 17.6 (Teutonico and Knorr 1985, Becker et al. 1981, Lorenz and Gross 1984, Sanchez Marroquin et al. 1986, Pedersen et al. 1987, Correa et al. 1986). Amaranth grain is reported to have high levels of lysine, a nutritionally critical amino acid, ranging from 0.73 to 0.84% of the total protein content (Bressani 1987a). The limiting amino acid is usually reported to be leucine (Singhal and Kulkarni 1988), although some reports indicate that threonine actually may be the amino acid which is more biologically limiting than leucine (Bressani 1987b).

The potential complimentary nature of amaranth protein has been studied by combining amaranth with wheat (Pant 1985), sorghum (Pedersen 1987) and maize (Tovar and Carpenter 1982; Sanchez Marroquin and Maya 1985). Ordinary maize meal supplemented with as little as 12.7% (by weight) of toasted amaranth flour provides a nutritionally superior source of protein that can satisfy a good portion of the protein requirement of young children, and provide approximately 70% of diet energy (Morales et al. 1988). A combination of rice and amaranth in a 1:1 ratio has been reported to approach the FAO/WHO protein specifications (Singhal and Kulkarni 1988).

The starch component of amaranth is distinctive. The starch granules are polygonal, measure 1 to 3 mm in diameter, and have a high swelling power (Stone and Lorenz 1984). There is a distinctive gel characteristic to the starch (Yanez et al. 1986). Waxy and non-waxy starch granules have been identified (Konishi et al. 1985). Interest has been expressed in specialized food and industrial applications for amaranth starch as a result of its distinctive characteristics.

Amaranth grain contains 6 to 10% oil, which is found mostly within the germ (Betschart et al. 1981, Lorenz and Hwang 1985, Garcia et al. 1987a). It is predominantly an unsaturated oil (76%) and is high in linoleic acid, which is necessary for human nutrition. In analyses conducted at the USDA Western Regional Research Center, amaranth oil was found to have 7% squalene, which is much higher than the amounts found in other common vegetable oils. Squalene, a high priced material, is usually extracted from shark livers and used in cosmetics (Lyon and Becker 1987).

Due to the fact that grain amaranth has high protein, as well as a high fat content, there is the potential to use it as an energy food. Using milled and toasted amaranth products, digestion and absorption was found to be high in human feeding studies (Morales et al. 1988). The balance of carbohydrates, fats, and protein, allow amaranth the opportunity to achieve a balanced nutrient uptake with lower amounts of consumption than with other cereals. It has been noted (Morales et al. 1988) that high protein rice is the only other cereal which has been cited to satisfy protein and energy needs.

Animal feeding studies (Betschart et al. 1981, Saunders and Becker 1984) indicate relatively high protein qualities. However, in some studies, weight gains were much lower than would have been expected (Cheeke and Bronson 1980, Afolbi and Oke 1981) for reasons that are not clear.

The digestibility and the protein efficiency ratio are improved if the grain is heat processed (Bressani et al. 1987b, Garcia et al. 1987b, Mendoza and Bressani 1987, Pant 1985, Sanchez Marroquin et al. 1985). The removal of lectins by heat processing has been reported to improve the protein efficiency ratio of the amaranth flour (Singhal and Kulkami 1988). There are a number of viable methods for processing, including popping, flours milled from toasted grain, heat-rolled flakes, extrusion, and wet cooking as a gruel. Excessive thermal processing has been shown to reduce the quality of amaranth grain (Bressani and Elias 1986). The potential for reducing nutritional quality is most evident when amaranth grain is processed using hot dry heat (as in toasting or popping).

An interesting application for amaranth is to use it as a food for people with allergies to other grains. The seed of "grain" amaranth is not a grain from a cereal plant, but is rather a pseudocereal from a dicotyledonous plant. It is unrelated to any other food crops that are commonly consumed, which makes it less likely to cause problems to people who have built up allergies due to repeated consumption of the same foods. Grain-free recipes which include amaranth flour have been published (Jones 1984).

In the USA, many amaranth products are being produced by specially companies which cater to the health-conscious market. Amaranth has been successfully processed in combination with other grains to produce cold, breakfast cereals. It is also being used for mixes that are used to prepare hot breakfast cereals and pancakes. In addition, there are breads, crackers and pastes on the market. Popped amaranth grain continues to attract considerable attention. The popped grain provides opportunities for processors to develop innovative products.

Grain amaranth is a new crop that is in its adolescence. The cultivation and utilization of grain amaranth will continue to increase as more information is developed to exploit the market niches for high quality protein foods.

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Fig. 1. Amaranth for use as a food colorant is planted as a dooryard crop in the Urubamba Valley of Peru.

Fig. 2. Amaranth used as a grain produces a light-colored seed.

Fig. 3. Grain amaranth lines with an improved plant habit are being developed for farmers in North America.

Fig. 4. Grain amaranth production in western Nebraska.

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