ISSN: 2230-9926

Available online at http://www.journalijdr.com

IJDR

International Journal of Development Research
Vol. 13, Issue, 08, pp. 63555-63574, August, 2023
https://doi.org/10.37118/ijdr.27087.08.2023

REVIEW ARTICLE OPEN ACCESS

ORIGIN, DOMESTICATION, TAXONOMY, BOTANICAL DESCRIPTION, GENETICS AND CYTOGENETICS, GENETIC DIVERSITY, BREEDING OF AMANRANTHS (*Amaranthus* spp.)

***KRM Swamy**

Retired Principal Scientist & Head, Division of Vegetable Crops, ICAR- Indian Institute of Horticultural Research, Bengaluru-560089

ARTICLE INFO

Article History:
Received 20th June, 2023
Received in revised form
21st July, 2023
Accepted 11th August, 2023
Published online 29th August, 2023

KeyWords:

Amaranths, Origin, Domestication, Taxonomy, Botanical Description, Genetic Diversity, Breeding.

Corresponding author: KRM Swamy

ABSTRACT

Amaranthus is a genus of food plants (*Amaranthus*) belonging to the family Amranthaceae. *Amaranthus* spp. or known as amaranth is a genus belonging to Amaranthaceae that includes 60–75 species. It is distinguished as the grain, vegetable, and weed or weedy types. The Amaranthacea comprise over 60 genera, which include around 800 species of dicotlyledonous, herbaceous plants, of either annual or perennial growth. The genus *Amaranthus* comprises 70 species. It shows a wide variety of morphological diversity among and even within certain species. The genus *Amaranthus* is rather unique in having species which are used for grain, vegetable and ornamental purposes. Amaranth is one of the few plants whose leaves are eaten as a vegetable while the seeds are used in the same way as cereals; there is no distinct separation between the vegetable and grain types since the leaves of young plants grown for grain can be eaten as both human and animal food. There are two basic types of amaranths: **1) Leaf amaranths/ greens amaranths**: Some are very attractive, looking like Coleus. The crop is ready in 50 days after sowing. The foliage is very nutritional- high in vitamin A, C, iron, calcium and protein. Harvests vary widely depending on variety and growing conditions. Generally speaking, "greens" means vegetable leaves that are eaten cooked. **2) Grain/ seed amaranths**: They closely resemble a cereal-type grain and can be treated as such. Amaranth grain is high in protein and other nutrients and can be harvested and cooked like rice or popped like popcorn. Although amaranth has only recently gained popularity as a health food, this ancient grain has been a dietary staple in certain parts of the world for millennia. It has an impressive nutrient profile and been associated with a number of impressive health benefits. The crop is widely distributed in India. It is cultivated in seventeen states of India *viz*., Jammu and Kashmir, Himachal Pradesh, Uttaranchal, North Bihar, Sikkim, Assam, Meghalaya, Arunachal Pradesh, Nagaland, Tripura, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Kerala, Tamil Nadu and Orissa. Information on the statistics on area and production of Amaranth in India is lacking. To date, the genetic improvement of amaranths has primarily involved the application of conventional selection methods. But advances in genomics and biotechnology have dramatically enriched the potential to manipulate the amaranth genome, especially improving the amount and availability of nutrients. In this Review Article Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Breeding, Uses, Nutritional Value and Health Benefits of Amanranths (*Amaranthus* spp.) are dicussed.

Citation: *KRM Swamy. 2023.* "Origin, domestication, taxonomy, botanical description, genetics and cytogenetics, genetic diversity, breeding of amanranths (*Amaranthus* spp.) ". *International Journal of Development Research*, 13, (08), 63555-63574.

INTRODUCTION

Amaranthus spp. or known as amaranth is a genus belonging to Amaranthaceae that includes 60–75 species. It is distinguished as the grain, vegetable, and weed or weedy types (Andini *et al.,* 2021). The Amaranthacea comprise over 60 genera, which include around 800 species of dicotlyledonous, herbaceous plants, of either annual or perennial growth (Bressani , 2003). *Amaranthus* is a genus of food plants (*Amaranthus*) belonging to the family Amranthaceae. The genus *Amaranthus* comprises 70 species. It shows a wide variety of morphological diversity among and even within certain species. The genus *Amaranthus* is rather unique in having species which are used for grain, vegetable and ornamental purposes (Pal 1999). There are two basic types of amaranths:

1) Leaf amaranths/ greens amaranths: Some are very attractive, looking like Coleus. The crop is ready in 50 days after sowing. The foliage is very nutritional- high in vitamin A, C, iron, calcium and protein. Harvests vary widely depending on variety and growing conditions. Generally speaking, "greens" means vegetable leaves that are eaten cooked (Geri, 1984).

2) Grain/ seed amaranths: They closely resemble a cereal-type grain and can be treated as such. Amaranth grain is high in protein and other nutrients and can be harvested and cooked like rice or popped like popcorn. Although amaranth has only recently gained popularity as a health food, this ancient grain has been a dietary staple in certain parts of the world for millennia. It has an impressive nutrient profile and been associated with a number of impressive health benefits.

The crop is widely distributed in India. It is cultivated in seventeen states of India *viz.*, Jammu and Kashmir, Himachal Pradesh, Uttaranchal, North Bihar, Sikkim, Assam, Meghalaya, Arunachal Pradesh, Nagaland, Tripura, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Kerala, Tamil Nadu and Orissa *(*Shodhganga 2018*).* Information on the statistics on area and production of Amaranth in India is lacking. *Amaranthus* is a cosmopolitan genus of annual or short-lived perennial plants collectively known as amaranths. Some amaranth species are cultivated as leaf vegetables, pseudocereals, and ornamental plants. Catkin-like cymes of densely packed flowers grow in summer or fall. Amaranth varies in flower, leaf, and stem color with a range of striking pigments from the spectrum of maroon to crimson and can grow longitudinally from 1 to 2.5 metres tall with a cylindrical, succulent, fibrous stem that is hollow with grooves and bracteoles when mature. There are approximately 75 species in the genus, 10 of which are dioecious and native to North America with the remaining 65 monoecious species endemic to every continent (except Antarctica) from tropical lowlands to the Himalayas. Amaranth grain is collected from the genus. The leaves of some species are also eaten (Wikipedia, 2023a**)**. "Amaranth" derives from Greek *amárantos*, "unfading", with the Greek word for "flower", *ánthos*, factoring into the word's development as *amaranth, the unfading flower*. *Amarant* is an archaic variant. The name was first applied to the related *Celosia* (*Amaranthus* and *Celosia* share long-lasting dried flowers), as *Amaranthus* plants were not yet known in Europe (Wikipedia, 2023a**)**. Grain amaranth's commercial production in the United States began in the late 1970s, grew through the 1980s, and has fluctuated since then. The yearly U.S. planting in the 1990s has been very small, typically in the 800 to 1,200 ha range. In the past 10 years, amaranth also has been grown for grain use in Iowa, Minnesota, North Dakota, Montana, Kansas, Pennsylvania, and in other scattered locations. Production of grain amaranth also is reported in a growing number of countries around the world, including China, India, Kenya, Mexico, Nepal, Peru, Russia, and several Eastern European countries. The largest area of the grain-type amaranth is in China, where 150,000 ha are reportedly grown for forage use (Vidhi, 2023). Vegetable types of amaranth are used across Africa, Asia, and the Americas. Amaranthus dubius, A. cruentus and A. tricolor are adapted for growth as leafy vegetables in areas with hot climates and especially in the hot, humid tropics where torrential rains during the monsoon season can create hazards for agriculture (Vidhi, 2023).

Amaranth is called as *chaulai* (Uttar Predesh and Bihar), *rajara* (Gujarat), *chuka* (Bengal), *kala ghasa, chumera* and *ganhar* (Central India), *shravani maath* (Maharashtra), *kolabhaji* (Mumbai), *seol, cholai* and *sil* (Northern Plains), *keerai* and *cheera* (Kerala), *harive*, *keere soppu* (Karnataka), *malan cheerai* and *mulaikkira / mullukurai* (TamilNadu), *bathu* (Shimla), *siriara* (Kulu), *tulsi, dankar* and *kalgi* (Kinnaur), *chua* (Kumaun Hills), *marschu* (Garhwal), *khada saga* (Orissa). There are at least three names for grain amaranth in Sanskrit: *rahadri, rajagiri* and *rajashakini (*Shodhganga 2018*).* Amaranth is one of the few plants whose leaves are eaten as a vegetable while the seeds are used in the same way as cereals; there is no distinct separation between the vegetable and grain types since the leaves of young plants grown for grain can be eaten as both human and animal food. When the leaves are harvested in moderation, the grain yield is unaltered. Vegetable amaranth species are utilized for food in different parts of the world. Grain amaranth can be used as seeds or flour to make products such as cookies, cakes, pancakes, bread muffins, crackers, pasta and other. The common names used for amaranth in different parts of India are, *ramdana, chaulai* (John *et al.*, 2008). Both the leaves and the seeds of amaranth are valuable in terms of human health. Whether one chooses to consume it as a leaf vegetable, a cereal grain or grain flour depends on what health benefits one is seeking out. Leaves and stems are interesting vegetable suitable for soups, salads or other meals. Amaranth is a nutritious, gluten-free grain that provides plenty of fiber, protein and micronutrients. It has also been associated with a number of health benefits, including reduced inflammation, lower cholesterol levels and increased weight loss. Best of all, this grain is easy to prepare and can be added to a variety of dishes, making it an excellent addition to your diet (Rachael, 2018). Nowadays amaranth sprouts and micro-greens are also being used as nutrition and health foods.

To date, the genetic improvement of amaranths has primarily involved the application of conventional selection methods. But advances in genomics and biotechnology have dramatically enriched the potential to manipulate the amaranth genome, especially improving the amount and availability of nutrients (Das, 2016). Out of thousands of edible plants, only three cereals—maize, wheat and rice—are the major food sources for a majority of people worldwide. While these crops provide high amounts of calories, they are low in protein and other essential nutrients. The dependence on only few crops, with often narrow genetic basis, leads to a high vulnerability of modern cropping systems to the predicted climate change and accompanying weather extremes. Broadening our food sources through the integration of so-called orphan crops can help to mitigate the effects of environmental change and improve qualitative food security. Thousands of traditional crops are known, but have received little attention in the last century and breeding efforts were limited. Amaranth is such an underutilized pseudo-cereal that is of particular interest because of its balanced amino acid and micronutrient profiles. Additionally, the C_4 photosynthetic pathway and ability to withstand environmental stress make the crop a suitable choice for future agricultural systems. Despite the potential of amaranth, efforts of genetic improvement lag considerably behind those of major crops. The progress in novel breeding methods and molecular techniques developed in model plants and major crops allow a rapid improvement of underutilized crops. In this Review Article Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Breeding, Uses, Nutritional Value and Health Benefits of Amanranths (*Amaranthus* spp.) are dicussed.

ORIGIN AND DOMESTICATION

The grain amaranth ('ramdana', 'marcha', 'ganhar', lathe') considered by many as the crop of the future has been associated with man since prehistoric times (4,800 BC). The genus *Amranthus* is notable mainly because of the success of many of its members as fellow-travelers of mankind. Sometimes deliberately cultivated as grain crops, green vegetables, dye plants, or ornamentals, more often unintentionally encouraged weeds, many amaranth species have spread and diversified with the advance of artificial habitats on every continent (Sauer, 1957). *Amaranthus*, collectively known as amaranth, is a cosmopolitan genus of annual or short-lived perennial plants. Some amaranth species are cultivated as leaf vegetables, cereals, and ornamental plants. Most of the species from *Amaranthus* are summer annual weeds and are commonly referred to as pigweeds. Catkin-like cymes of densely packed flowers grow in summer or autumn. Approximately 60 species are recognized, with inflorescences and foliage ranging from purple and red to green or gold. Members of this genus share many characteristics and uses with members of the closely related genus *Celosia* (WIKI, 2015). Amaranth is a grain with high nutrition value, comparable to those of maize and rice. Amaranth has been a staple in Mesoamerica for thousands of years, first collected as a wild food, and then domesticated at least as early as 4000 BC. The edible parts are the seeds, which are consumed whole toasted or milled into flour. Other uses of amaranth include dye, forage and ornamental purposes. Amaranth is a plant of the family of Amaranthaceae*.* About 60 species are native to the Americas, whereas less numerous are the species originally from Europe, Africa and Asia. The most widespread species are native of North, Central and South America, and these are A. Cruentus, A. caudatus, and A. hypochondriacus. Amaranthus cruentus, and A. hypochondriacus are native of Mexico and Guatemala. The first one is used in Mexico to produce typical sweets called alegría**,** in which the amaranth grains are toasted and mixed with honey or chocolate. Amaranthus caudatus is a widely distributed staple food both in South America and in India.

This species originated as one of the staple foods for the ancient inhabitants of the Andean region (Sauer, 1967; Maestri, 2015). Some species of green amaranth (*Amaranthus* spp.), especially, *Amaranthus gangeticus*, *A. mangostanus*, *A. paniculatus, A. angustifolius,* are supposed to have originated in India or Indo-Chinese region. Other spiecies have originated in various other centres like North America, Central America, Mexico, South America and Mediterranean region (Nath and Swamy, 2015). The main cultivated species of vegetable type Amaranthus - *A. tricolor* L., has been originated in South or Southeast Asia, particularly in India. hot season vegetable, it is cultivated throughout the year in the tropics (Varalakshmi, 2015) (Fig. 1).

The cultivated species of grain type *Amaranthus* and their probable native regions are as follows (Sauer, 1986) (Fig. 2):

- *Amaranthus hypochondriacus* (= *A. frumentaceus, A. leucocarpus*, *etc*.) of Northwestern and Central Mexico.
- *A. cruentus* (= *A. paniculatus*, *etc.*) of Southern Mexico and Central America.

A. blitum

A. cruentus

A. dubius

A. spinosus

A. tricolor

A. viridi

Fig. 1. Cultivated species of vegetable type *Amaranthus*

A.caudatus

A. hypochondriacus

A. cruentus

Fig. 2. Cultivated species of grain type *Amaranthus*

Buddhist monks and Muslim invaders took the crop to neighboring countries. Another vegetable type, *A. dubius* L., shows diversity in Central America, Indonesia, India and in Africa. *A. lividus* seems to have been a popular vegetable in Southern and Central Europe. As a

A. caudatus of the Andes. In the Argentine Andes, the typical form is grown together with a conspicuous mutant that produces club-shaped inflorescence branches with determinate growth, a trait unknown in wild Amaranths. This mutant has commonly been given specific rank (as *A. edulis*) but may better be treated as *A. caudatus* ssp. *mantegazzianus.*

The wild species that appear most closely related to the above grain type species are as follows (Sauer, 1986):

- *A. powellii*, a pioneer of canyons, desert washes and other open habitats in the Western Cordillera of the Americas. An aberrant form with indehiscent utricles has sometimes been given specific rank as *A. bouchonii.*
- *A. hybridus* (= *A. chlorostachys, A. patulus, etc.*), a riverbank pioneer of moister regions of Eastern North America and the mild highlands of Central America.
- *A. quitensis*, a riverbank pioneer of highland and subtropical South America.

Amaranths were probably widely used among hunter-gatherers in both North and South America. The wild seeds, even if small in size, are produced in abundance by the plant and are easy to collect. Evidence of domesticated amaranth seeds comes from the Coxcatlan cave in the Tehuacan valley of Mexico and dates as early as 4000 BC. Coxcatlan Cave is a rockshelter in the Tehuacan Valley of Mexico, and it was occupied by humans for nearly 10,000 years. Later evidence, like caches with charred amaranth seeds, has been found throughout the US Southwest and the Hopewell culture of the US Midwest. Domesticated species are usually larger and have shorter and weaker leaves which make the collection of the grains simpler. As other grains, seeds are collected through rubbing the inflorescences between the hands (Sauer, 1967; Maestri, 2015). Amaranth grain has a long and colorful history in Mexico and is considered a native crop in Peru. It was a major food crop of the Aztecs, and some have estimated amaranth was domesticated between 6,000 and 8,000 years ago. During the pre-Columbian period, the Aztecs cultivated amaranth as a staple grain crop. Annual grain tributes of amaranth to the Aztec emperor were roughly equal to corn tributes. The Aztecs did not just grow and eat amaranths, they also used the grains as part of their religious practices. Many ceremonies would include the creation of a deity's image that had been made from a combination of amaranth grains and honey. Once formed, the images were worshipped before being broken into pieces and distributed for people to eat. But things changed when the Spanish conquistadors (adventurers or conquerors, especially one of the Spanish conquerors of the New World in the 16th century) arrived. The conquistadors (one that conquers) were Spanish explorers and warriors who successfully conquered much of America in the 16th century. When Cortez and his Spaniards landed in the New World in the sixteenth century, they immediately began fervent and often forceful attempts to convert the Aztecs to Christianity. One of their first moves was to outlaw foods involved in "heathen" festivals and religious ceremonies, amaranth included. Although severe punishment was handed to anyone found growing or possessing amaranth, complete eradication of this culturally important, fast-growing, and very prevalent plant proved to be impossible (Anon., 2015b).

Evolution is change in heritable traits of biological populations over successive generations. Evolutionary processes give rise to diversity at every level of biological organisation, including the level of species, individual organisms, and at the level of molecular evolution. Evolution can be defined as a process of gradual and relatively continuous change from a lower, simpler, or worse to a higher, more complex, or better state/growth. It is the historical development of a biological group (as a race or species (phylogeny). It is a theory that the various types of animals and plants have their origin in other pre-existing types and that the distinguishable differences are due to modifications in successive generations (WIKI, 2015a). Whatever their origin, the grain *Amaranthus* species arose from a wild progenitor or progenitors by domestication. Grain types are not found in the wild condition anywhere in the world. The principles involved during a long selection history resulted, firstly, in the development of rather short and weak bracts, in order to make the inflorescence less prickly when rubbed between the hands while extracting grain. The perfectly dehiscent utricle has been an added advantage in this direction. Secondly, selection has been made for large plant body, particularly large compound inflorescences, so as to give enormous grain yield without an increase in grain size. Thirdly, there has been a decided preference for white seeds with good popping qualities and flavor. During these selection processes, there has been inadvertent selection for the right proportions of protein, carbohydrate and oil components to make it a balanced food with higher calorific value. These features also distinguish the grain types from their wild ancestors (Pal and Khoshoo, 1973a; Sauer, 1967).

Amaranths once held prominent roles in the religious, agricultural, and economic activities of pre-Columbian civilizations including Aztec, Maya, and Inca. Seeds of *Amaranthus* species often turn up in prehistoric caches throughout Mesoamerica and elsewhere in the United States, some dated to at least 5,000–7,000 years ago. However, the extent to which certain amaranths were cultivated or other species harvested in the wild remains debatable based on available evidence. Phylogenetic evidence suggests the history of cultivated amaranths may involve multiregional and incomplete domestication with frequent and ongoing gene flow with wild relatives. Seed color appears to be one trait of domesticated species, with pale-colored seeds found only in certain cultivated varieties and black seeds being more common within the genus. Regardless, the cultural importance of amaranths in pre-Hispanic societies was such that Spanish conquerors felt the need to forbid their consumption and ceremonial use. Nonetheless, amaranth cultivation endured despite centuries of suppression. This once-prominent food crop is now experiencing a resurgence in popularity as a highly nutritious and resilient 'ancient grain' for modern diets within and beyond its native region (Riggins and Mumm, 2023).

TAXONOMY

Amaranthus spp. or known as amaranth is a genus belonging to Amaranthaceae that includes 60–75 species. It is distinguished as the grain, vegetable, and weed or weedy types (Andini *et al.,* 2021). The Amaranthacea comprise over 60 genera, which include around 800 species of dicotlyledonous, herbaceous plants, of either annual or perennial growth. There are three species of the genus *Amaranthus* that produce relatively large inflorescences with often more than 50 000 edible seeds per plant. These are A. hypochondriacus from Mexico, A. cruentus from Guatemala and A. caudatus from Peru and other Andean countries. Vegetable amaranths grow very well in the hot, humid regions of Africa, South-east Asia, Southern China, and India; they are represented by various amaranth species, such as A. tricolor, A. dubius, A. cruentus, A. edulis, A. retroflexus, A. *viridis*, and A. hybridus**.** Grain amaranth was an important crop for the preHispanic, New World civilizations. Its presence goes back some 4000 years bc in the Tehuacan Valley in Mexico, also the most likely site for the origin of maize. Its use is said to have been highly associated with religious festivities, which were forbidden by the Spanish conquerors and resulted in the elimination of the crop. Its production declined to small and insignificant levels, but it did not disappear. From Mesoamerica and the Andean region, grain amaranth was apparently carried as a weed, ornamental, or grain to other parts of the world (Bressani, 2003). Amaranths produce minuscule flowers typically borne in dense inflorescences atop a central stem or at the ends of branches that can persist long after the plant dies, hence the origin of the genus name from the Greek word for 'immortal' or 'unfading'. Taxonomic and biogeographic studies of the genus can be challenging due to high phenotypic plasticity, intergrading forms, and the possibility of natural hybrids. Misidentifications are not uncommon in herbaria, literature, and even genebanks, further complicating our understanding of the genus (Riggins and Mumm, 2023). Amaranth is the common name for more than 60-70 different species of *Amaranthus*, which are usually very tall plants with broad green leaves and impressively bright purple, red, or gold flowers. The name for amaranth comes from the Greek *amarantos*, "one that does not wither," or "the never-fading." True to form, amaranth's bushy flowers retain their vibrancy even after harvesting and drying, and some varieties of ornamental amaranth forego the production of fancy flowers in favor of flashy foliage, sprouting leaves that can range from deep blood-red to light green shot with purple veining. Although several species can be viewed as little more than annoying weeds, people around the world value amaranths as leaf vegetables, cereals, and ornamental plants (Anon., 2015b).

Amaranth belongs to the family Amaranthaceae and the genus *Amaranthus.* The *Amaranthus* genus (Magnoliophyta: Caryophyllidae) comprises 70 species grouped into three subgenera (Mosyakin and Robertson 2003). *Amaranthus* shows a wide variety of morphological diversity among and even within certain species. Although the family Amaranthaceae is distinctive, the genus has few distinguishing characters among the 70 species included. This complicates taxonomy and *Amaranthus* has generally been considered among systematists as a "difficult" genus. Formerly, Sauer (1955) classified the genus into two subgenera, differentiating only between monoecious and dioecious species: *Acnida* and *Amaranthus*. Although this classification was widely accepted, further infrageneric classification was (and still is) needed to differentiate this widely diverse group. Currently, *Amaranthus* includes three recognized subgenera and 70 species, although species numbers are questionable due to hybridization and species concepts. Infrageneric classification focuses on inflorescence, flower characters and whether a species is monoecious or dioecious, as in the Sauer (1955) suggested classification. A modified infrageneric classification of *Amaranthus* was published by Mosyakin and Robertson (1996) and includes three subgenera: *Acnida*, *Amaranthus*, and *Albersia*. The taxonomy is further differentiated by sections within each of the subgenera (WIKI, 2015). Sauer (1967) recognize two sections in *Amaranthus, viz.*, *Amaranthus* and *Blitopsis,* with equal number of species in each. Section *Amaranthus* consists of species having terminal flower clusters and includes grain types; whereas section *Blitopsis* consists of species having flower clusters in axils and includes the green types or vegetable types

The most economically important is the subgenus *Amaranthus* proper, which includes the three species domesticated for grain production *viz., Amaranthus hypochondriacus, Amaranthus cruentus,* and *Amaranthus caudatus.* Other species of amaranths have been domesticated as leaf-vegetables, for fodder, as potherbs, or as ornamentals; among these species, A. *tricolor,* from South Asia, is probably the most important (Sauer 1967). According to Ebert *et al.* (2011) the genus *Amaranthus* comprises about 70 species, 40 of which are native to the Americas. Among the 70 species, 17 are vegetable amaranths with edible leaves, and three are grain amaranths with edible seeds (*A. caudatus*– Inca wheat, love-lies-bleeding; *A. cruentus*– purple amaranth; *A. hypochondriacus*– Prince's feather). There are several species of *Amaranthus* used for leaves, grains or for both. There is a taxonomic confusion because species are quickly adapted in any environment, differences among various species are small, many specific and common names have been used throughout the world, almost interchangeably and also due to quick intergradation of a species in the region itself where it thrives well when cultivated and appears adapted. In spite of this confusion, some species are sufficiently recognized to merit universal acceptance.

The best of the species for grains is *A. hypochandriacus* L. and for edible leaves *A.gangeticus* L., *A. cruentus* L and *A. dubius* Mart ex. Thell. *A. hypochandriacus* was used as a grain in India and Sri Lanka in the 18th century. It became prevalent in the foot hills of the Himalayas during the 19th century, where it became a staple food. It is important now in Nepal, China, Manchuria, Uganda, *etc*. In India, *A. hypochandriacus* and *A. caudatus (*grains) and *A. gangeticus* (leaves) are of major importance. *A. mangostanus* (Syn. *A. tricolor* var *mangostanus), A. lividus* and *A. dubius (*a recognized tetraploid) are grown on a limited scale in Orissa and other states (Nath and Swamy, 2015). The important species of leafy amaranth, *Amaranthus tricolor* L, occupies a predominant position in India with different morphological forms in colour and shape of leaves. *Amaranthus dubius, A. lividus, A. blitum, A tristis* L., *A. spinosus* L and *A. viridis* are other amaranth species, which are under cultivation. *Amaranthus* is an annual herb, erect or trailing, scarce to profuse branched, shallow to deep tap-rooted, stem green to purple, leaf simple, alternate or opposite, colour green to purple. Inflorescence terminal and axillary, branched spikes, flower small, regular, mostly unisexual, monoecious. In general the cultivated species are monoecious (Nath and Swamy, 2015).

Amaranth is an annual plant with C4 type of photosynthesis. Depending on species amaranth leaves vary in shape, size and colour (green, red, purple). This plant can grow up to 3 m. Its stem, sometimes branched, is terminated by branched inflorescence (panicle). Inflorescence is usually indeterminate and reaches different lengths. Basic unit in inflorescence is called glomerule containing female, male or both florets. Seed has lenticular shape (1-2 mm). Amaranth shows a high coefficient of propagation (Anon., 2015a) (Fig. 3). Amaranthus comes in three forms: 1) Plume (such as 'Hot Biscuits' or 'Velvet Curtains'), 2) Hanging or tassels (such as the quintessential red 'Love-Lies-Bleeding'), and 3) Spike (such as 'Elephant Head').

Inflorescence of amaranth

Seed heads of amaranth

Fig. 3. Inflorescence and seed head of amaranth

Sauer (1957) studied a group of ten related North American species, sharply set off from all other amaranths of the world by their dioecious habit. He made an attempt to reconstruct some of their history. This group is more open to such reconstruction than most of the genus because its distribution and heredity were less radically reshaped by ancient man. None of the dioecious amaranths have become domesticated plants or pandemic weeds. Yet, they have also been increasing in geographic and genetic ranges in response to civilization. Tracing their comparatively plain case histories may be a fair approach to understanding the behavior of the whole genus. He reported that the ten dioecious species of *Amaranthus*, all originally pioneer plants of naturally disturbed habitats, have behaved quite differently during increasing human disturbance of their native continent, North America. Those at home in coastal marshes, beaches, and dunes have remained static while those from river floodplains and desert washes have been expanding and diversifying as weeds in artificially opened habitats. Direct historical evidence, mainly from a hundred year record of herbarium collections, permits partial reconstruction of the geographic and genetic changes. The amount of geographic advance has been very unequal even along different borders of a single species. In some cases expansion was local and completed before the present century; elsewhere migration has extended across whole states and is still active. However, unlike the common weedy monoecious amaranths, even the weediest dioecious species have remained geographically cohesive. With geographic expansion, former limited overlap between species has greatly deepened and exceptional hybridization has become common. Apparent hybrids derived from a large number of species pairs, involving not only all the dioecious but also some monoecious species. Crosses between dioecious and monoecious species run into a blind alley of sterility but crosses among dioecious species have yielded fertile off-spring, in some cases so abundantly that the taxonomic distinctness of the parent species is threatened. Hybrid populations are almost invariably concentrated in the newer, artificial habitats, perhaps because of less rigorous selection in such places. In natural habitats the older types of populations have remained relatively immune to invasion and hybridization. The genus *Amaranthus* L. (Amaranthaceae) comprises 70–80 species worldwide with the greatest diversity found in warm-temperate to tropical zones. The majority of amaranth species are native to the Americas, but some taxa have greatly extended their distribution far beyond their native region. Amaranths are herbaceous annuals or short-lived perennials and are mostly monoecious (bearing both male and female floral organs separately on the same plant), although dioecy (bearing male and female floral organs on different individual plants) appears to have originated independently in a small group of species native to North America. Amaranth species are easy-to-grow, strikingly attractive plants that exhibit an impressive display of betalain-derived pigmentation patterns spanning yellow, orange, and crimson hues (Riggins and Mumm, 2023) (Fig. 4).

Fig. 4. Variety of amaranth pigmented phenotypes from the USDA's amaranth germplasm collection

Species include (Wikipedia, 2023a):

1) *Amaranthus acanthochiton* – greenstripe
2) *Amaranthus acutilobus* – a synonym of *Amaranthus viridis*[18]
3) *Amaranthus albus* – white pigweed, tumble pigweed
4) *Amaranthus anderssonii*
5) *Amaranthus arenicola* – sandhill amaranth
6) *Amaranthus australis* – southern amaranth
7) *Amaranthus bigelovii* – Bigelow's amaranth
8) *Amaranthus blitoides* – mat amaranth, prostrate amaranth, prostrate pigweed
9) *Amaranthus blitum* – purple amaranth
10) *Amaranthus brownii* – Brown's amaranth
11) *Amaranthus californicus* – California amaranth, California pigweed
12) *Amaranthus cannabinus* – tidal-marsh amaranth
13) *Amaranthus caudatus* – love-lies-bleeding, pendant amaranth, tassel flower, *quilete*
14) *Amaranthus chihuahuensis* – Chihuahuan amaranth
15) *Amaranthus crassipes* – spreading amaranth
16) *Amaranthus crispus* – crispleaf amaranth
17) *Amaranthus cruentus* – purple amaranth, red amaranth, Mexican grain amaranth
18) *Amaranthus deflexus* – large-fruit amaranth
19) *Amaranthus dubius* – spleen amaranth, *khada sag*
20) *Amaranthus fimbriatus* – fringed amaranth, fringed pigweed
21) *Amaranthus floridanus* – Florida amaranth
22) *Amaranthus furcatus*
23) *Amaranthus graecizans*
24) *Amaranthus grandiflorus*
25) *Amaranthus greggii* – Gregg's amaranth
26) *Amaranthus hybridus* – smooth amaranth, smooth pigweed, red amaranth
27) *Amaranthus hypochondriacus* – Prince-of-Wales feather, prince's feather
28) *Amaranthus interruptus* – Australian amaranth[20]
29) *Amaranthus minimus*
30) *Amaranthus mitchellii*
31) *Amaranthus muricatus* – African amaranth[21]
32) *Amaranthus obcordatus* – Trans-Pecos amaranth
33) *Amaranthus palmeri* – Palmer's amaranth, Palmer pigweed, careless weed
34) *Amaranthus polygonoides* – tropical amaranth
35) *Amaranthus powellii* – green amaranth, Powell amaranth, Powell pigweed
36) *Amaranthus pringlei* – Pringle's amaranth
37) *Amaranthus pumilus* – seaside amaranth
38) *Amaranthus quitensis* - Mucronate Amaranth
39) *Amaranthus retroflexus* – red-root amaranth, redroot pigweed, common amaranth
40) Amaranthus saradhiana
41) *Amaranthus scleranthoides* – variously *Amaranthus sclerantoides*
42) *Amaranthus scleropoides* – bone-bract amaranth
43) *Amaranthus spinosus* – spiny amaranth, prickly amaranth, thorny amaranth
44) *Amaranthus standleyanus*
45) *Amaranthus thunbergii* – Thunberg's amaranth
46) *Amaranthus torreyi* – Torrey's amaranth
47) *Amaranthus tricolor* – Joseph's-coat
48) *Amaranthus tuberculatus* – rough-fruit amaranth, tall waterhemp
49) *Amaranthus viridis* – slender amaranth, green amaranth
50) *Amaranthus watsonii* – Watson's amaranth
51) *Amaranthus wrightii* – Wright's amaranth

BOTANICAL DESCRIPTION

The Amaranthaceae consist of annual or perennial, hermaphroditic, dioecious, monoecious, or polygamous herbs, vines, shrubs, or rarely trees. The stems are sometimes jointed or succulent. The leaves are simple, spiral or opposite, ex stipulate, succulent or reduced in some taxa. The inflorescence is of solitary flowers or a spike, panicle, cyme, or thyrse, with bracts and bracteoles bristle-like and pigmented in some taxa. Spikes are borne at the tip of the stem and in the axils of the leaves. The individual spikes have a bristly appearance because of the linear bracts surrounding the flowers. Small male (staminate) and female (pistillate) flowers are found on the same plant. Each flower has five pink sepals and no petals. The flowers are small, bisexual or unisexual, usually actinomorphic, hypogynous or rarely epihypogynous. The perianth is uniseriate (usually termed a calyx, by default), consisting of [0–2] 3–5 [6–8] distinct or rarely basally connate sepals. The stamens are [1–2] 3–5 [6–8], generally the same number as sepals and antisepalous, distinct or basally connate and forming a tube. Anthers are longitudinal in dehiscence, dithecal or monothecal. The gynoecium is unicarpellous or syncarpous, with a superior, rarely half-inferior ovary, 1–3 [5] carpels, and 1 locule. The style**(s)** are 1–several. Placentation is basal; ovules are campylotropous or amphitropous, bitegmic, 1 [∞]. Nectaries are present in some, typically an annular disk. The fruit is a nutlet, berry, irregularly dehiscing capsule, or rarely a circumscissile capsule or multiple fruit. The seeds are mostly starchy-perispermous with curved embryo. Betalain pigments are present, anthocyanins absent. Plants have anomalous secondary growth, forming concentric rings of vascular bundles or alternating concentric rings of xylem and phloem, often with C4 or CAM photosynthesis. The Amaranthaceae are distinctive in being herbs to trees with *anomalous secondary growth***,** simple leaves (succulent to reduced in some), bristlelike, pigmented bracts in some, a *uniseriate perianth* of mostly 3–5 [0–2, 6–8] sepals, basally connate stamens of same number and opposite perianth parts, a *1-loculed, mostly 1-ovuled* ovary with *basal* placentation, seeds with *curved embryo*, and betalain pigments only present (Fig. 5) (Simpson*,* 2010).

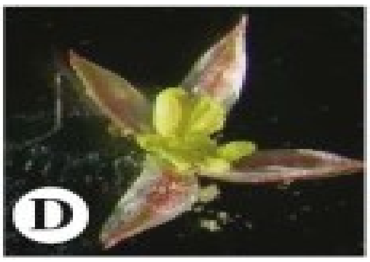
 Young plant	 Young plant	 Bundle for sale
 Bundle for sale	 Infloracens	 Infloracens
 Female flower	 Male flower	 Infloracens
 Grains	 Grains	 Grains
 Plants in glass house	 Field	 Field
 Seeds	 Seeds	 Seeds

Fig. 5. Botanical Description

Amaranth is a herbaceous plant or shrub that is either annual or perennial across the genus. Flowers vary interspecifically from the presence of 3 or 5 tepals and stamens, whereas a 7-porate pollen grain structure remains consistent across the family. Species across the genus contain concentric rings of vascular bundles, and fix carbon efficiently with a C4 photosynthetic pathway. Leaves are approximately 6.5–15 centimetres and of oval or elliptical shape that are either opposite or alternate across species, although most leaves are whole and simple with entire margins. Amaranth has a primary root with deeper spreading secondary fibrous root structures. Inflorescences are in the form a large panicle that varies from terminal to axial, color, and sex. The tassel of fluorescence is either erect or bent and varies in width and length between species. Flowers are radially symmetric and either bisexual or unisexual with very small, bristly perianth and pointy bracts. Species in this genus are either monecious (*e.g. A. hybridus,*) or dioecious (*e.g. A. palmeri*). Fruits are in the form of capsules referred to as a *unilocular pixdio* that opens at maturity. The top (operculum) of the unilocular pixdio releases the urn that contains the seed. Seeds are circular form from 1 to 1.5 mm in diameter and range in color with a shiny, smooth seed coat. The panicle is harvested 200 days after cultivation with approximately 1,000 to 3,000 seeds harvested per g (Wikipedia, 2023a).

Stigma of pistillate flower is receptive several days prior to opening of staminate flowers in an inflorescence. Wind help in transfer of pollen grains from male flowers of a glomerule / inflorescence / plant to another glomerule / inflorescence / plant. But grain species with colorful inflorescence are occasionally visited by bees (Fig. 6) (Eagri, 2023a). The three grain-producing species (*A. caudatus, A. cruentus*, and *A. hypochondriacus*) have differences in agronomic performance. *Amaranthus caudatus* is grown at high elevations in South America and Asia and most accessions of it are prone to diseases and late maturity in the temperate zone. Its flowers have short bracts so that the inflorescence is not bristly, its spreading styles are separated by a ‘U’-shaped cleft, and the sepals are obtuse. *Amaranthus cruentus* is the most photoperiod insensitive and widely-adapted grain species. Its flowers also have short bracts, but its styles are vertical and parallel. *Amaranthus hypochondriacus* has been adapted to temperate photoperiods by plant breeders and is not disease prone. Its flowers have bracts that roughly equal the height of the styles, making the inflorescence bristly. Its styles join with a V-shaped cleft.

Fig. 6. Inflorescences of selected Amaranthus species. a Apical and axillary inflorescences of A. blitum; b Hanging inflorescence of *A. caudatus*; c Terminal inflorescence of *A. cruentus*; d Terminal inflorescence of *A. dubius*; e Inflorescence of *A. hypochondriacus*; f Apical and axillary inflorescences of *A. spinosus*; g Axillary clusters of *A. tricolor*; h Terminal

Amaranth is an annual herb with erect growth and scarce to profuse branching habit. Stem is succulent and green or purple or mixed shades of these two. Leaf is simple, alternate, with obviate to lanceolate shape. Leaf colour is green or red or with different shades of above. Flowers are borne terminally and in axils of leaves in clusters. Basic unit of inflorescence is called as glomerule. Flowers are small, unisexual and monoecious. Most of cultivated types are monoecious. Proportion of male and female flowers varies in an inflorescence. Each glomerule consists of a staminate flower and a number of pistillate flowers. The extent of cross pollination is governed by proportion of male and female flowers in an inflorescence and position of inflorescence in plant. Percentage of male flowers in a glomerule is 0.5 in grain types and 10.25 in leaf types. Leaf amaranths are predominantly self pollinated due to presence of a large number of male flowers per glomerule, terminal inflorescence and development of axillary glomerules. Grain types favour cross pollination.

Two of the cultivated vegetable accessions from Bangladesh (PI 606281 and PI 606282) are presently identified as *Amaranthus aff. blitum* in the GRIN on-line database. The flowers closely resemble *A. blitum*, but the growth form is erect and single stemmed, and the leaves are red-purple as is found in *A. tricolor*. *Amaranihus caudatus* includes a distinctive plant type with an orange determinate inflorescence. However, some authors regard it as a separate species, either *A. edulis* Speg. or *A. mantegazzianus* Pass. In the RRC type system it is *edulis*. The USDA, ARS (1999) database lists *A. caudatus* subsp. *mantegazzianus* (Pass.) Hanelt, as a synonym of *A. caudatus* (Vidhi, 2023).

Floral Biology of Amaranth: Most amaranth species are monoecious. The flowers can be terminal or axial, but are always organized into glomerulus within the inflorescence. Within the glomerules the first flower is generally staminate, and the later flowers are pistillate. There are two kinds of exceptions to the usual monoecious pattern: the dioecious species and two species (A. spinosus and A. dubius) with separate staminate and pistillate glomerules within the inflorescence (Vidhi, 2023).

Cross-pollination Procedures: Controlled crossing in greenhouses has been used successfully at the RRC. Crossing amaranths requires positioning or agitating synchronously flowering plants, so that when pollen is released, it will fall on the styles of the seed parent. Genetic markers can be used to distinguish hybrids from the plants resulting from self-pollination. Inter-specific hybrids are usually distinctive enough that markers are not needed. The red/green trait is easily used, but other markers are also available. It is possible to emasculate, but if genetic markers are available, they are easier to use and more reliable. Crossing is most easily accomplished in a greenhouse because plants in pots can be easily moved; photoperiods can be manipulated to synchronize flowering, and unwanted pollen can be excluded. However, adapted types that have synchronized flowering will cross naturally between adjacent field rows (Vidhi, 2023).

GENETICS AND CYTOGENETICS

Most *Amaranthus* species are n = 16 or n = 17, but *A. dubius* is unusual for having n = 32. The grain amaranths are paleo-allotetraploids, as indicated by observations of pairing in their hybrids. These studies of pairing behaviour could be expanded to include more of the grain amaranth races and perhaps explain their erratic patterns of cross-compatibility. Outside of the grain amaranths, pairing behaviour has been studied for only a few of potential crosses (Vidhi, 2023). Chromosome number varies with species in amaranth. The diploid species have 2n=32 or 34. A tricolor is with 2n=34, while A. cruentus and A. tristis have 2n=32. The tetraploid species, A dubius has 2n=64 (Eagri, 2023a**).** For evaluating the genetic diversity between wild and cultivated species and assessing the evolutionary relationships between the cultivated species and their putative species using wide array of available markers. A wide morphological variability between *Amaranthus* species and different accessions of vegetable *Amaranthus* was reported. This variability was useful in cultivar improvement for agronomic traits. The chromosome number for *Amaranthus* species is normally 2n=32 (n=16), but occasionally it is 34 (n=17). It has been suggested that the gametic number n=17 has originated from n=16 through trisomy. Karyotypes are mainly comprised of many metacentric chromosomes and few submetacentric ones. There is a variation in chromosome size between *Amaranthus* spp. and the accessions of each species. Based on cytological data, it was proposed that *A. hybridus* is the putative ancestors of the cultivated amaranths. Buffer extracts of seed storage proteins of taxa of *Amaranthus* spp. analyzed on SDS-PAGE under reducing conditions divided *Amaranthus* taxa into two groups; group with n=17 and the other group with n=16, indicating the relation between the chromosome number and the electrophoretic pattern. The electrophorectic patterns of the seed proteins of amaranth species can be used to discriminate between *Amaranthus* species. Isozymes markers showed low heterozygosity in the New World populations of *Amaranthus*. A wide genetic distance was detected between crop and weed species. Alleles at several loci proved to be diagnostic of the crop and weed groups. High levels of interspecific and intraspecific variation were found between *Amaranthus* spp. using isozyme marker. Biochemical and molecular data sets supported a monophyletic origin of grain amaranths, with *A. hybridus* as the common ancestor. The molecular data showed genetic variation among and within the populations of *Amaranthus* spp. and indicated that genetic diveristy within wild was lower than grain species (Sammour *et al.,* 2012).

GENETIC DIVERSITY

Seed colors can vary from cream to gold and pink to black. The tiny, lens shaped seeds are usually pale in colour. They frequently have a pale yellowish colour with an occasional tinge of magenta pigment. Seed shape varying from conical, cylindrical or ellipsoidal in shape. The seed is rounded at both ends, or egg shaped (i.e. ovate or obovate, broader at one end). Rounded, symmetrical about the middle or broader below the middle or broader above the middle. Seed size varies in diameter from 0.9 to 2.5 mm. According to Sauer (1986) wild amaranth seeds were commonly gathered by many prehistoric American Indian people. The wild seeds are as nutritious and as large as those of the cultivated species. Archaeological proof of domestication comes with the appearance of pale white seeds, contrasting starkly with the dark brown wild type; the mutation producing this change has never been recorded historically. Associated with the change in colour are improved popping quality and flavor. A small proportion of dark seeds is generally present in the grain crops. Where selection for pale seed colour is relaxed, as when the plants are grown as ornamentals, the dark seeds became predominant. The earlier record of the pale-seeded crop is from Tehuacan, Puebla, Mexico, where *A. cruentus* appeared about 4,000 BC and was joined by *A. hypochondriacus* about AD 500. By the 14th century AD, pale-seeded *A. hypochondriacus* was also cultivated by Arizona cliff-dwellers. The earliest record of *A. caudatus* is from 2,000-year-old tombs in Northwestern Argentina, where its pale seeds were found mixed with those of *Chenopodium quinoa* and with dark seeds of weed amaranths and chenopods. The three grain type species may have been independently domesticated but there is an alternative possibility, namely that there was a single primary domestication of *A. cruentus* from *A. hybridus*, with the other two domesticates evolving secondarily by repeated crossing of *A. cruentus* with weedy *A. powellii* and *A. quitensis* as the crop spread into their respective territories. Evolution of all three domesticates has involved increased size of the whole plant and particularly of the inflorescence, resulting in greatly increased seed yield. All three domesticates also display the effects of selection for striking anthocyanin pigmentation of leaves, stem and inflorescences. Presumably, the intense red colour had ceremonial meaning. At the time of the Spanish Conquest, grain amaranths were important in rituals of the Aztecs and other Mexican peoples. Judging by later ethnographic evidence, ceremonial use of red amaranths extended from the Pueblo region of the Southwestern United States to the Andes and was more widespread than use as a grain crop. The ceremonial dye amaranths are generally extremely deep red forms of *A. cruentus* with dark seeds; in the Andes some may be *A. cruentus X A. quitensis* hybrids. Different colored seeds of Amaranthus are available (Fig. 7).

Putnan (1992) stated that crops are truly artifacts of human history. We can ask ourselves this: "What would Africans do without peanuts, the Indians do without chillies, the Irish or Poles do without potatoes, the Italians do without tomatoes or the whole world do without maize?". All were new crops from Americas (as is amaranth). Each of these species found an important role in the culture of the society to which they were transported, and filled an important need or niche not previously met by an 'Old' crop. Crops such as amaranth became only a curiosities in Europe largely because those cultures did not discover ways to easily incorporate the crop into their diet; the grains of amaranth were too small to be easily ground by primitive flour mills. Initial mistrust may have also played a role, as it did with the tomato. Such was not the case in the introduction of amaranth to India centuries ago. Not only amaranth is grown by farmers at the highest habitable regions of the Himalayas, but it is grown in arid regions of the plains and throughout the Indian subcontinent. It is eaten as a leafy vegetable or popped as a candy, "chikki". Amaranth is widely adapted and reasonably high yielding. Amaranth is cited in ancient religious texts and has many Indian names. It is hypothesized that amaranth found its way to Surat and South India *via* Portuguese traders, and eventually made its way to the Himalayas. In the Indian subcontinent, amaranth is still very much an underutilized crop. The tradition here dictates eating habits, and amaranth is not widely utilized in daily diets. In many Indian Institutes, research on amaranth is being carried out for decades. In Spanish America or Hispanic America (the region comprising the Spanish-speaking nations in the Americas) after the 16th century, grain Amaranth cultivation was regarded as a symbol of paganism and repressed; thus the crop nearly disappeared from history. However, by the early 19th century, grain

Amaranths had appeared as a staple food crop in the Nilgiri Hills of South India and in the Himalaya; they have since been noted over an increasingly wide area of India as well as across the interior of China to Manchuria and Eastern Siberia. Pale-seeded *Amaranthus hypochondriacus* constitutes the bulk of Asiatic crop; dark-seeded *A. hypochondriacus* and pale-seeded *A. caudatus* are minor components. In the 1940s, cultivation of *A. hypochondriacus* was begun in East Africa to supply grain to the local Indian population.

by using matK and simple sequence repeats (SSR) markers. Our phylogenetic analysis based on the matK marker classified the species of 68% of the accessions, of which 120 belonged to A. tricolor.

We developed 21 SSR markers, which amplified a total of 153 alleles in 294 A. tricolor accessions originating from Vietnam and overseas, with a mean allelic richness of 7.29 per marker, observed heterozygosity of 0.14, expected heterozygosity of 0.38, and

Fig. 7. Variability for seed color, shape and size in *Amaranthus*

The wide latitudinal spread of these species in the Old World presumably required evolutionary changes, because their flowering is controlled by photoperiod. *A. cruentus* has not become established as a grain crop in the Old World. However, dark-seeded, deep red forms of this species have been widely planted in tropical Africa and Asia for over a century as ornamentals, dye plants, fetishes and potherbs. All these three of the domesticated species may have been introduced to the Old World via Europe; they have been grown in European gardens as ornamentals and curiosities for at least 250 years. Only dark-seeded forms of *A. hypochondriacus* were known to have present in Europe (Sauer, 1986). Leafy amaranths, which are consumed as traditional food in Asia and Africa, are now considered among the most promising vegetables. In Vietnam, leafy amaranths, particularly *Amaranthus tricolor* L., are important summer vegetables due to their excellent nutritional values and high tolerance to biotic and abiotic stresses. However, this species has not been subjected to systematic breeding. Here we describe species identification and evaluation of the genetic diversity of Vietnamese amaranth collection

polymorphic information content of 0.35. The STRUCTURE and F_{ST} analysis indicated a positive relationship between geographic distance and genetic differentiation among most of the overseas groups and the Vietnamese collection, but not among geographic groups within the Vietnamese collection. Vietnamese amaranths could be divided into two major types, one common in East Asia and the other one unique to Vietnam (Nguyen *et al.,* 2019). Random Amplified Polymorphic DNA (RAPD) markers were used to investigate genetic diversity and phylogenetic relationships among 10 species belonging to the genus Amaranthus L. The results showed that the polymorphism in cultivated species was lower than that in wild ones, reflecting the selection pressures of domestication on genetic diversity in cultivated species. A specific RAPD marker was detected for each of A. powellii PI 572262, A. tricolor PI 462129**,** A. palmeri PI 607455, A. caudatus PI 511679 and A. quitensis PI 511744. The overall mean similarity index of amplified fragments generated by RAPD primers on genomic DNA of Amaranthus accessions indicated that A. hypochondriacu**s** was the closest grain amaranth to A. hybridus, followed by A. caudatus and A. cruentus**.** A. tricolor had a maximum genetic distance from grain amaranth species, confirming its morphological classification in a distinct subgenus Albersia**.** Similarly, the accessions of A. palmeri were separated in a distinct cluster, supporting its classification in a distinct subgenus Acnida. A. hybridus accessions were gathered together with grain amaranth species, thereby supporting the single progenitor hypothesis for grain amaranths. A. spinosus was separated on a distinct principal coordinate axe, indicating its low correlation with other species and confirming its morphological classification in a distinct section, i.e. Centrusa (Sammour *et al.,* 2020). *Amaranthus* (Amaranthaceae) generally known as amaranth is an annual herbaceous genus, grown under diverse agro-climatic conditions. It has many species carrying nutraceutical properties with the potential to add values to the food, cosmetic, and pharmaceutical industries. According to their usage, amaranths are broadly classified into the grain, vegetable, weed, and wild type. This helps in the understanding of intra- and inter-specific diversity present in amaranths, evaluated by morphological, biochemical, cytological, and molecular approaches. The understanding of genetic diversity in amaranth breeding programs support in identifying diverse parents to generate segregating population with genetic variability for introgression of desired agronomic traits and to develop high yielding elite varieties of amaranth (Dharajiya et al., 2021). Within the genus, a high genetic variation exists and this is perceived as a result of outcrossing and plant hybridization that promotes gene exchange and introgression between wild relatives. Outcrossing rate in amaranth is ranging from 5 to 30% and this unique characteristic would have enabled the hybridization in amaranth, distinctively among the weedy ones (Andini *et al*., 2021).

Black amaranth (*Amarantus quitensis* Kunth) is an ancestral crop of the Ecuadorian Andean region, where traditionally it is called ataco or sangorache. Nowadays, there is some information about the phenotypic diversity of black amaranth landraces, but there are no data about their genetic diversity. In this study, we evaluated the genetic diversity of 139 black amaranth accessions collected twice in three representative Ecuadorian Andean provinces for this crop (Imbabura, Tungurahua, and Cañar) using nine simple sequence repeats (SSR) markers. We detected low genetic diversity levels; only a total of 36 alleles were amplified in 139 accessions, with a mean allelic richness of 4.0 per marker, observed heterozygosity of 0.014, expected heterozygosity of 0.134, and Shannon’s information index of 0.297. In addition, only 17 genotypes were found, with a predominant genotype (83.6%) and up to 12 accession-unique genotypes. Moreover, a certain genetic diversity decrease was observed over the last decades, especially in Tungurahua and Cañar, where today practically only the predominant genotype exists. The ataco germplasm is genetically structured into two well-defined genotype clusters and could constitute two different genetic lineages. Furthermore, a clear association of each genotype group with a different color morphotype defined in a previous agromorphological characterization was observed. The accessions of the majority group of genotypes showed purple pigmentation in stems, leaves, and inflorescences, whereas those of the other genotype group showed less intense pigmentation (pink stems, inflorescences, and green leaves) (Delgado and Martín, 2023).

Amaranthus retroflexus L. and *Chenopodium album* L. (Amaranthaceae) are weedy plants that cause severe ecological and economic damage. In this study, we collected DNA from three different countries and assessed genetic diversity using inter-simple sequence repeat (ISSR) markers. Our analysis shows both weed species have low genetic diversity within a population and high genetic diversity among populations, as well as a low value of gene flow among the populations. UPGMA clustering and principal coordinate analysis indicate four distinct groups for *A. retroflexus* L. and *C. album* L. exist. We detected significant isolation-by-distance for *A. retroflexus* L. and no significant correlation for *C.*album L. These conclusions are based data from 13 ISSR primers where the average percentage of polymorphism produced was 98.46% for *A. retroflexus* L. and 74.81% for *C. album* L.These data suggest that each population was independently introduced to the location from which it was sampled and these noxious weeds come armed with considerable genetic variability giving them the opportunity to manifest myriad traits that could be used to avoid management practices (Moghadam *et al.,* 2023).

BREEDING

Germplasm: At present, there are three major germ plasm collections: (1) USDA Plant Introduction Center, Ames, Iowa, US; (2) Universidad del Cuzco, Cuzco, Peru; (3) National Bureau of Plant Genetic Resources, Shimla, India (Bressani , 2003). Much untapped genetic diversity is present in local landraces and wild relatives. Amaranth germplasm collections are maintained in various repositories worldwide, including the US (USDA), Mexico (INIFAP), India (ICAR-NBPGR), Madagascar (FOFIFA), and WorldVeg (AVRDC), with many recognized species and varieties available through commercial sources. Genomic resources, including newly published whole genomes, transcriptomes, and various other datasets, are also available for cultivated amaranths and several weedy species. Altogether, these resources will facilitate interdisciplinary research for more resilient crops, improved weed management and human health (Riggins and Mumm, 2023). Amaranthus germplasm has been collected for ex situ conservation. Most collections have less than 100 accessions, but six collections have substantial numbers of accessions (Table 1). Amaranthus is well suited to ex situ conservation because the seeds are long lived and small (Vidhi, 2023).

Table 1. The six large ex situ amaranthus germplasm collection

No. accessions	Institute
438	Institute of Crop Germplasm Resources (CAAS) Beijing, China
440	Universidad Nacional del Altiplano Puno, Peru
495	Instituto Nacional de Investig. Forestalesy Agropecuarias (INIFAP) Col. San Rafael, Mexico
740	Univ. Nacional San Antonio Abad del Cuzco (UNSAAC/CICA) Cuzco, Peru
3,000	National Bureau of Plant Genetic Resources (NBPGR) Regional Station, Shimla, India
3,380	North Central Regional Plant Introduction Station (NCRPIS) Ames, Iowa, United States

Breeding Objectives of Amaranth (Vidhi, 2023)

Grain Amaranths*:*

1. Raising yield
2. Increasing harvest-ability
i. Lodging resistance
ii. Less seed shattering
iii. Timing of maturity
iv. Uniformity of maturity
v. Reduced leafiness in the green head area
vi. Reduced plant height
3. Good seedling vigour
4. Pest resistance/tolerance
i. Tarnished plant bug or sucking insect (Lygus lineolaris)
ii. Stem boring insect (Hypolixus)
iii. Damping off
iv. Phomopsis
5. Larger seeds
6. Good nutritional profile of seed (high seed protein, 14-16%)
7. Tolerance to cold

Vegetable Amaranths:

i. Heat tolerance
ii. Improved seedling establishment
iii. Resistance to diseases, insects and drought

Breeding: Breeding mechanism in amaranths is highly variable due to variability and versatility of inflorescence ratio and distribution of male and female flower in inflorescence and variability of matting system ranging from obligate out-crossing, relatively greater outcrossing to relatively greater self-pollination. Several useful breeding traits have been identified in amaranths like, increased seed protein, resistance to seed shattering, increased seed size, reduced plant height and high yield, improved pest resistance etc. The work on genetic improvement has been done so far mostly applying conventional selection method from cultivars, landraces, hybrids with genetic variability. Several new improved varieties have been developed. Hybrids between grain and weed amaranths have been produced to address all major breeding objectives including biomass heterosis, transfer of herbicide resistance and non-dehiscence properties. Male sterility identified in certain grain species (*A. hypochondriacus*) could be very handy to simplify the hybridization process. Beside conventional breeding methods, application of non-conventional breeding strategies like induced mutation breeding techniques, genetic engineering and biotechnological approaches are gaining importance. Genetic variability created in useful trait by induced mutation followed by selection has become a routine practice in amaranth breeding.

Few mutant varieties of amaranth have been established and released officially like – Centenario in Peru, New Asutake in Japan, and Sterk in Russia. Technological innovation in plant biotechnology is an important catalyst in crop improvement. *Agrobacterium*-mediated transformation technique has been standerdized in amaranth which has opened up a new avenue to transfer useful gene like – Oxalate decarboxylase gene to reduce the level of oxalic acid in vegetable amaranth which is a known antinutrient. Storage seed albumin protein *AmA1* has been characterized from *A. hypochondriacus* and the protein gene has been successfully cloned and transferred to potato showing a tuber specific expression. Marker Assisted Selection (MAS) and molecular breeding has helped to generate knowledge regarding transfer of simply inherited quantitative traits from genetic resources into elite cultivars also to understand the molecular control of target trait of interest. Molecular markers like SSRs, RFLPs, ISSRs found effective to distinguish genetically similar accessions and to determine individual degree of heterozygosity and heterozygosity within plant genetic resource populations. Though studies on in vitro growth and morphogenesis of amaranth are scanty, but such studies are gaining momentum (Das, 2016).

Vegetable amaranth (*Amaranthus* sp.), a leafy vegetable crop consumed around the world, is actively promoted as a source of essential micronutrients to at-risk populations. Such promotion makes micronutrient content essential to the underlying value of this crop. However, the extent to which micronutrient content varies by effect of genotype is not clear, leaving breeders uninformed on how to prioritize micronutrient contents as the criteria for selection among other performance parameters. A total of 32 entries across seven *Amaranthus* species were field-grown and analyzed for Fe, Mg, Ca, Zn, yield, height, and canopy spread comprising 20 entries at New Jersey in 2013; 12 entries at Arusha, Tanzania, in 2014; and 20 entries at New Jersey in 2015. The genotype effect was significant in all trials for Fe, Mg, Ca, Zn, total yield, marketable yield, height, and canopy spread. The Fe content range was above and below the breeding target of 4.2 mg/100 g Fe in all environments except for New Jersey 2015, where all entries were found to accumulate in levels below the target. All entries in each of the environments contained levels of Ca and Mg above breeding targets, 300 mg/100 g Ca and 90 mg/100 g Mg. None of the entries in any environment met the Zn breeding target of 4.5 mg/100 g Zn (Byrnes *et al*., 2017). Opportunities abound for improving amaranth yield and nutritional profiles through targeted breeding and biotechnology. Several breeding programs in Africa are underway to create improved, locally adapted varieties for grain and vegetable production including CENRADERU-FOFIFA in Madagascar, ARC in South Africa, and NHRI and Lagos State University in Nigeria. Furthermore, chemical diversity among wild and weedy relatives is yet to be explored (Riggins and Mumm, 2023).

Qualitative Genes: Numerous major genes have been identified that may be useful for breeding. A few important ones are listed in Table 2.

Table 2. Major genes in *Amaranthus*

Trait	Gene symbol	Source
Embryo color		
Pink/pale	*Pe/pe*., homozygous oo prevents expression of Pe	*A. caudatus*
Flowering		
Male fertile/male sterile	*Ms1/ms1*	*A. hypochondriacus*
Cytoplasmic inheritance of male sterility	*S1/S2* cytoplasm types *Rf1/rf1*, *Rf2/rf2*, *Rf3/rf3* nuclear genes	*A. hypochondriacus*
Normal/all female		*A. cruentus*
Early flowering (temperate)/ late flowering (tropical)		*A. sp.* × *A. hybridus*
Early flowering/late flowering	*Ea/ea*	*A. retroflexus* × *A cruentus*
High male frequency/normal		*A. hypochondriacus*
Herbicide tolerance		
Triazine tolerant/not tolerant	With chloroplast	*A. hybridus*
Hybridization barrier		
Abnormal hybrids/ normal hybrids	*Ah1/ah1*, *Ah2/ah2*	*A. caudatus* × *A. hypochondriacus*
Inflorescence architecture		
Indeterminate/determinate	*Dt/dt*	*A. caudatus*
Indeterminate/determinate	One gene from PI 584523 *Pd1/pd1*, *Pd2/pd2* and modifying factors	A caudatus
Leaf and other markings]		
Blade V-mark/no V-mark	*Vm1/vm1*, *Vm2/vm2*	*A hypochodriacus*, *A. retroflexus*
Blade spot/no spot	*Ls/ls*	*A hypochondriacus*
Blade red vein/green	*R1/r*	*A. tricolor*
Blade red vein/green	*R2/r*	*A. tricolor*
Blade pale red/green	*R3/r*	*A. tricolor*
Blade both surfaces red /green	*R4/r*	*A. tricolor*
Blade red /green	*A/a*, *B/b*, *C/c*	*A. tricolor*
Blade no-spot/non-green spot (without chlorophyll)	*T/t*	*A. tricolor*
Stem green/white (without chlorophyll)	one gene	*A. tricolor*
Stem green/white (without chlorophyll)	*B/b* (pink = *A* below with *b*) *A/a*	*A. tricolor*
Perianth colour/ intermediate/green	partial dominance	*A. caudatus*
Inflorescence red/green	One gene	Various
Perisperm type		
Glutinous/non-glutinous, ("Glutinous" is not the same gluten as in wheat, so the terms opaque/translucent, or waxy/non-waxy are preferred)	*Gl/gl*	*A. caudatus*, *A. cruentus* *A. hypochondriacus*
Pigmentation		
Red/green	R/r	Several
Red/green	*R/r*	*A. tricolor*
Orange/green	*O/o*	*A. caudatus* and *A. cruentus*
Chlorophyll present/ absent (lethal)	three genes	*A. caudatus* × *A. hypochondriacus*
Normal/chlorophyll variegation		*A. caudatus* × *A. hypochondriacus*
Yellow (flavinoid)/non-yellow	C/c	*A. tricolor*
Red seedling/flowering	*Lp/lp*	*A. caudatus*, *A. hypochondriacus*
Red whole plant/base of plant only	*Bd/bd*	Various
Red normal/diminished	One gene	*A. caudatus*
Red not intense/intense	One gene	Various
Seed coat color		
Black/pale	*P/p*	*A. caudatus*, *A. hypochondriacus*
Yellow/pale	*Y/p*	*A caudatus*, *A. hypochondriacus*
Brown/pale	*Br/br*	*A caudatus*
Black/dark-med-light Brown/pale	2 genes	*A. cruentus* *A. retroflexus*
Shattering		
Dehiscent/indehiscent	*Dh/dh*	*A. hypochondriacus*
Dehiscent/indehiscent	More than one gene	*A. cruentus*
Nonpersistent utricles/persistent	Few genes	Various
Vegetative architecture		
Tall/dwarf	Dwarf is recessive	*A. hypochondriacus*
Cotyledon long/short	Multiple genes	*A. caudatus*
Tall/dwarf	*Dw/dw*	*A. caudatus*
Normal blade/oak leaf shape	*Ok/ok*	*A. cruentus* × *A. retroflexus*
Narrow blade/normal	*V/v*	*A. tricolor*

Breeding Methods

Breeding mechanism in amaranths is highly variable due to variability and versatility of inflorescence ratio and distribution of male and female flower in inflorescence and variability of matting system ranging from obligate out-crossing, relatively greater outcrossing to relatively greater self-pollination. Several useful breeding traits have been identified in amaranths like, increased seed protein, resistance to seed shattering, increased seed size, reduced plant height and high yield, improved pest resistance etc. The work on genetic improvement has been done so far mostly applying conventional selection method from cultivars, landraces, hybrids with genetic variability. Several new improved varieties have been developed. Hybrids between grain and weed amaranths have been produced to address all major breeding objectives including biomass heterosis, transfer of herbicide resistance and non-dehiscence properties. Male sterility identified in certain grain species (*A. hypochondriacus*) could be very handy to simplify the hybridization process. Beside conventional breeding methods, application of non-conventional breeding strategies like induced mutation breeding techniques, genetic engineering and biotechnological approaches are gaining importance. Genetic variability created in useful trait by induced mutation followed by selection has become a routine practice in amaranth breeding. Few mutant varieties of amaranth have been established and released officially like – Centenario in Peru, New Asutake in Japan, and Sterk in Russia. Technological innovation in plant biotechnology is an important catalyst in crop improvement. Agrobacterium-mediated transformation technique has been standerdized in amaranth which has opened up a new avenue to transfer useful gene like – Oxalate decarboxylase gene to reduce the level of oxalic acid in vegetable amaranth which is a known antinutrient. Storage seed albumin protein AmA1 has been characterized from *A. hypochondriacus* and the protein gene has been successfully cloned and transferred to potato showing a tuber specific expression. Marker Assisted Selection (MAS) and molecular breeding has helped to generate knowledge regarding transfer of simply inherited quantitative traits from genetic resources into elite cultivars also to understand the molecular control of target trait of interest. Molecular markers like SSRs, RFLPs, ISSRs found effective to distinguish genetically similar accessions and to determine individual degree of heterozygosity and heterozygosity within plant genetic resource populations (Das, 2016). Amaranths can be vegetatively propagated from stem cuttings by using commercial rooting hormones. Finally, there is extensive literature on tissue culture, and in vitro culture (Vidhi, 2023).

Mutations

Many Amaranthus species are highly self-pollinated, limiting variability within accessions. Spontaneous genetic variation is low in these amaranths indicating the potential to obtain useful variability with induced mutation techniques. Mutants with a basal branching habit could be of economic value for vegetable production because the higher number of branches could increase leaf harvests, especially with improved regrowth ability. The viable mutation frequency increased (2-8%) when the irradiation doses were increased (3-15 KR) for six Amaranthus genotypes tested, with the high doses yielding more early, and the lower doses more late- maturing mutants. Earliness could be advantageous for grain amaranths to escape drought and fit into crop rotations (Vidhi, 2023).

Genetic Engineering

To date, the genetic improvement of amaranths has primarily involved the application of conventional selection methods. But advances in genomics and biotechnology have dramatically enriched the potential to manipulate the amaranth genome, especially improving the amount and availability of nutrients. Beside conventional breeding methods, application of non-conventional breeding strategies like induced mutation breeding techniques, genetic engineering and biotechnological approaches are gaining importance (Das, 2016). The potential of amaranth in biotechnology and even if some work is already being carried out, it is necessary to increase research efforts towards these aspects. This section summarises and discusses research already done regarding tissue culture, molecular biology and genetic transformation of amaranth. It should be noted that genetic engineering comes as a modern and frontline application of biotechnology. The main streams that biotechnology touches are cell and tissue culture, genetic engineering, microbiology, embryology, molecular biology, and many others. Gulping beer, tasting wine, favourite chocolate, ever-loving ice cream, and many other products are proud results of biotechnology. The cultivation of food plants, producing high-yielding crops, antibiotics, enzymes, and hundreds of other products are also involved in biotechnology. Pharmacology, medicine, and other treating means are some of other areas that are being operated through biotechnology. Therefore, it is clear that there are umpteen applications created through biotechnology. It also has a great history that dates back almost towards the early days of human civilizations. Genetic materials of organisms can be altered using genetic engineering techniques or recombinant DNA technology. Recombinant DNA technology is the process used to create a recombinant DNA molecule which carries the DNA of interest and vector DNA while genetic engineering is a broad term used to describe the processes involved in manipulation of the genetic structure of an organism. This is the key difference between Genetic Engineering and Recombinant DNA technology (Kara Rogers, **2020;** WIKI, 2020). "GMOs- genetically modified organisms are any living entity constructed by altering their genetic composition, without affecting their normal function." In other words, it can be stated as, "Organisms whose genetic material is altered using the recombinant DNA technology or gene therapy is known as GMO or genetically modified organisms." GMOs are those whose genetic material is changed using genetic engineering techniques. Significant improvement in plant hybridization is done after the introduction of various sophisticated genetics and genomics techniques. The GMO stands for **"**genetically modified organism***"***, meaning that something from an organism's genome (plant, animal or bacteria) is changed or modified (Chauhan, 2020).

The aim of constructing GMOs is to either change organisms' characteristics or producing a new variation in nature. Those changes are actually beneficial to us- humans. For example, the insulin a type of protein is now produced using the recombinant DNA technology through the genetically modified bacteria. The genome of those bacteria is altered in such a way that as they grew, they produced insulin as a byproduct. GMOs have tremendous application in agriculture, medicine, human science and animal research likewise. Starting from primitive prokaryotes to higher eukaryotes, any living organism's genome can be altered using artificial means. Genetically modified plant species or bacterial strains are created for various applications (Chauhan, 2020). Genes from two organisms of the same species, different species or from different genera are linked or joined to construct the recombinant DNA. Using artificial vectors or plasmid, the newly formed DNA is inserted into the host organism. PCR, DNA sequencing and microarray are various techniques implemented to validate the insert (Chauhan, 2020).

Varieties of Amaranth (Vidhi, 2023).

Grain Type *(Vidhi, 2023):* Joshi (1985) developed 'Annapurna' from a selection program in India. Annapurna's average grain yield is 22.3 q/ha which is about 69% higher than that of another selection VL 21. The whitish creamy seeds of Annapurna contain about 14.5% protein. Its popping quality is excellent. The distinguishing features of Annapurna are as follows: 1) Plant height: 220-225 cm. 2) Flowering: 75 days. 3) Maturity: 140-145 days. 4) Stem: Stout, generally un-branched, ridged. 5) Foliage: Leaf broad, dark green, lanceolate (24 X 12 cm). 6) Inflorescence: Long (70 cm), green, compact terminal and lateral spikelet's. 7) Test weight: 0.8-0.9 g/1000 seeds. and 8) . Seed colour : Creamish white.

Vegetable Type *(Vidhi, 2023):* The nutritional value of vegetable amaranth has been extensively studied. The nutritional value has been rated equal or even superior to spinach, as it is considerably higher in calcium, iron, and phosphorous as well as fiber, niacin, and ascorbic acid on a fresh-weight basis and vitamin A, magnesium, and protein. In parts of Africa, where the diet of rural people is high in carbohydrate and low in protein, leafy amaranth is a good source of protein, and is used heavily. Vegetable amaranths provide a high concentration of vitamin A, which is important for preventing eye diseases in the tropics. Although vegetable amaranth contains oxalates and nitrates, they are not harmful for consumption under normal conditions of dietary intake. The levels of oxalates and nitrates are reduced by boiling the leaves. When grown under stressful conditions, vegetable amaranths produce higher levels of oxalate compounds, which could have adverse nutritional effects on humans or animals when utilized in quantities of more than 100 g of fresh greens daily. The main use of leafy amaranth is as a cooked vegetable whose leaves and soft shoot parts are boiled in several changes of water for 10-15 minutes. When cooked, the leaves of A. tricolor are similar to spinach, with a fine, smooth-textured taste. Sensory evaluation research done on amaranth entries from Asia and Africa showed that care must be taken in the choice of entries to be grown, as the eating qualities vary among species and selections, and that affects its acceptability as a vegetable crop. Vegetable amaranths have a wide diversity in growth habit, leaf shape, colour, and size, plant size, and inflorescence characteristics, but typically they have broad leaves and low seed production. The primary vegetable amaranths are *A. blitum*, *A. cruentus, A. dubius, A. tricolor* and *A. hypochondriacus*. Wild species are also commonly gathered as leafy vegetables. *Amaranthus cruentus*, *A. dubius*, and *A. tricolor* appear to be superior to other amaranth species for use as vegetables, as they have the highest leaf-stem ratio. Leaf-stem ratios and yields also vary dramatically between cultivars within species.

Improved Varieties released in India: Cultivated leaf amaranth varieties and cultivars differ in size, shape and colour of leaves and stem, position of inflorescence etc. and belong to different species. A brief description of improved varieties developed by different Research Institutes is given below (**Eagri, 2023a):**

Tamil Nadu Agricultural University, Coimbatore

CO. l (A. dubius**):** This tetraploid variety was developed by selection from ("local germplasm. Stem and leaves are dark green; leaf-stem ratio is 2.0; inflorescence terminal and axillary; lacks initial vigour but makes rapid growth after 30 days; suitable for late harvest; resistant to Rhizoctonia leaf blight; green yield 8.0 t/ha; seed yield 1.5 t/ha.

CO.2 (A. tricolor**):** Stem and leaves green, leaves lanceolate and slightly elongate, leaf-stem ratio 1.8; suited for early harvest; yield 10.78 t/ha.

CO.3 (A. tristis**):** This is specifically suited for clipping of tender greens and is locally known as 'Araikeera' in Tamil. Leaves are small and green; stem is slender and tender. First clipping is possible in 20 days after sowing. Nearly 10 clippings can be taken over a period of 90 days. Due to very high leaf-stem ratio, cooking quality and taste are excellent. Special care is required in land preparation for the variety.

CO. 4 (A.hypochondriacus): This grain type makes rapid vegetative growth within a period of 20-25 days. Plants are dwarf; grain yield 2.0-2.5 t/ha in 80-90 days.

CO.5 (A. tricolor**):** Leaves double coloured with Green and pink and is free from fibre. It gives a rosette growth in early stages and first harvest is possible in 25 days; yield 40 t/ha in 55 days.

Sirukeerai (A. polygonoides**)** is a traditional cultivar in Tamil Nadu, suited for uprooting at 25 days after sowing; leaves are small, ovate with blunt bifurcated tip and have long petiole; collar region is dark pink and at leaf axil a miniature branch initiates.

IARI, New Delhi

Pusa Chotti Chaulai (A. blitum**):** Plants dwarf with succulent, small and green leaves; responds well to cutting.

Pusa Badi Chaulai (A. tricolor**):** Plants tall and stem thick with large green leaves; responds to cutting.

Pusa Kirti (A. blitum**):** Green leaved variety with green and thick stem; leaf lamina broad ovate; ready for harvest in 30-35 days and extends up to 70-85 days; yield 55 t/ha; specifically suited for summer.

Pusa Kiran (A. tricolor**):** This is developed by natural crossing between A. tricolor and A. tristis and has more characteristics of A. **tricolor.** Leaves are glossy green with broad ovate lamina; leaf-stem ratio is 1.0:4.6; yield 35 t/ha in 70-75 days; suited for kharif season.

Pusa Lal Chaulai (A. tricolor**):** Upper surface of leaves are deep red and lower surface purplish red; yield 45-49 t/ha in 4 harvests.

IIHR, Bangalore

Arka Suguana (A. tricolor**):** A multicut variety with broad green leaves. First picking starts in 24 days after sowing and continue up to 90 days. Moderately resistant to white rust. Yield 17-18 t/ha.

Ark Arunima (A. tricolor**):**A multicult variety with broad dark purple leaves. First picking starts in 30 days after sowing and two subsequent cuttings at 10-12 days interval. Yield 27 t/ha.

USES

In all fairness to whole grains everywhere, we need to "out" amaranth as a bit of an imposter. It is not a true cereal grain in the sense that oats, wheat, sorghum, and most other grains are. "True cereals" all come from the Poaceae family of plants, while amaranth (among others) is often referred to as a "pseudo-cereal", meaning it belongs to a different plant species. So why are these invaders almost always included in the whole grain roundup? Because their overall nutrient profile is similar to that of cereals, and more importantly, pseudo-cereals like amaranth have been utilized in traditional diets spanning thousands of years in much the same way as the "true cereals" have been (Anon., 2015b). The genus *Amaranthus* is rather unique in having species which are used for grain, vegetable and ornamental purposes. Recently the potential of microcrystalline (1-3 µm) starch granules for possible replacement of talc in the cosmetic industry and edible dyes has emerged. The most common use in the major regions of its cultivation (Peru, Bolivia, Ecuador, Mexico, India, Nepal and Bhutan) is in the form of cakes or balls (laddoos) prepared by binding the popped seed in jiggery or sugar. The vegetable amaranths are used as pot herbs in most tropical countries of the world. While the related foliage ornamental types add colour to the otherwise drab garden surroundings in summer months (Pal, 1999). Vegetable amaranth is widely grown in the tropics and is one of the most important leafy vegetables in the lowlands of Africa and Asia. Amaranth is an annual, fast growing herb that can be cultivated easily in home gardens and at commercial scale (Ebert *et al*., 2011). Amaranth today is enjoyed many ways. In Mexico and India the seeds are popped and mixed with sugar to make a confection. In Mexico they are roasted for the traditional drink "atole." Peruvians use the grain to make a beer. Elsewhere it is used to treat toothache and fevers or to color maize and quinoa. Women performing native dances often wear the red amaranth flower as rouge. In many countries the leaves are used boiled or fried. In Nepal the seeds are made in to a gruel. Although amaranth seed and flour can be found in health food stores (Green Deane, 2012). Several species are raised for amaranth "grain" in Asia and the Americas. Amaranth and its relative quinoa are considered pseudo-cereals because of their similarities to cereals in flavor and cooking. The spread of *Amaranthus* is of a joint effort of human expansion, adaptation, and fertilization strategies. Grain amaranth has been used for food by humans in several ways. The grain can be ground into a flour for use like other grain flours. It can be popped like popcorn, or flaked like oatmeal. It has been proposed as an inexpensive native crop that could be cultivated by indigenous people in rural areas for several reasons (Wikipedia, 2023a):

- A small amount of seed plants a large area (seeding rate 1 kg/ha).

- Yields are high compared to the seeding rate: 1,000 kg or more per hectare.
- It is easily harvested and easily processed, post harvest, as there are no hulls to remove.
- Its seeds are a source of protein.
- It has rich content of the dietary minerals, calcium, magnesium, phosphorus, and potassium.
- In cooked and edible forms, amaranth retains adequate content of several dietary minerals.
- It is easy to cook. Boil in water with twice the amount of water as grain by volume (or 2.4 times as much water by weight). Amaranth seed can also be popped one tablespoon at a time in a hot pan without oil, shaken every few seconds to avoid burning.
- It grows fast and, in three cultivated species, the large seedheads can weigh up to 1 kg and contain a half-million small seeds.

Amaranth species are cultivated and consumed as a leaf vegetable in many parts of the world. Four species of *Amaranthus* are documented as cultivated vegetables in eastern Asia: *Amaranthus cruentus*, *Amaranthus blitum, Amaranthus dubius*, and *Amaranthus tricolor* (Wikipedia, 2023a**)**. In Uttar Pradesh and Bihar in India, it is called *chaulai* and is a popular red leafy vegetable (referred to in the class of vegetable preparations called *laal saag*). It is called *chua* in Kumaun area of Uttarakhand, where it is a popular red-green vegetable. In Karnataka in India, it is called *harive soppu.* It is used to prepare curries such as *hulee, palya, majjigay-hulee*, and so on. In Kerala, it is called *cheera* and is consumed by stir-frying the leaves with spices and red chili peppers to make a dish called *cheera thoran*. In Tamil Nadu, it is called *mulaikkira* and is regularly consumed as a favourite dish, where the greens are steamed and mashed with light seasoning of salt, red chili pepper, and cumin. It is called *keerai masial*. In the states of *Andhra Pradesh and Telangana* and other Telugu speaking regions of the country, this leaf is called as "*Thotakura*" and is cooked as a standalone curry, added as a part of mix leafy vegetable curry or added in preparation of a popular *dal* called *thotakura pappu* in (Telugu). In Maharashtra, it is called *shravani maath* and is available in both red and white colour. In Orissa, it is called *khada saga*, it is used to prepare *saga bhaja*, in which the leaf is fried with chili and onions. In West Bengal, the green variant is called *Notey Shaak and the red variant is called Laal Shaak* (Wikipedia, 2023a).

The genus also contains several well-known ornamental plants, such as *Amaranthus caudatus* (love-lies-bleeding), a vigorous, hardy annual with dark purplish flowers crowded in handsome drooping spikes. Another Indian annual, *A. hypochondriacus* (prince's feather), has deeply veined, lance-shaped leaves, purple on the under face, and deep crimson flowers densely packed on erect spikes. Amaranths are recorded as food plants for some Lepidoptera (butterfly and moth) species including the nutmeg moth and various case-bearer moths of the genus *Coleophora*: *C. amaranthella*, *C. enchorda* (feeds exclusively on *Amaranthus*), *C. immortalis* (feeds exclusively on *Amaranthus*), *C. lineapulvella*, and *C. versurella* (recorded on *A. spinosus*) (Wikipedia, 2023a**)**.

NUTRITIONAL VALUE

Amaranth is also making a comeback as a popular super food. The seed, commonly referred to as grain, is gluten-free and a good source of protein. It may also have a political advantage over quinoa, another healthy grain that is growing in popularity. Quinoa has drawn some controversy recently because the price of the grain has increased so dramatically that the indigenous populations in Bolivia, Ecuador, and Peru (where the grain is grown) can no longer afford to eat it. Some argue that the increased demand creates income for otherwise impoverished areas. Amaranth, on the other hand, is inexpensive in comparison to quinoa, and easily cultivated in a wider variety of conditions. It can survive in arid climates and is currently grown everywhere from Long Island and Iowa to India and Fiji. As a bonus, the plant's stems and leaves are also edible and vitamin-rich. In Caribbean cultures, certain varieties of amaranth leaves are known as *callaloo* (Wang, 2012). In true "never-fading" fashion, seeds from the amaranth plant spread around the world and both leaves and grain became important food sources in areas of Africa, India, and Nepal. In the past two decades, amaranth has reached a much larger number of farmers and can now be found in many non-native regions such as China, Russia, Thailand, and Nigeria, as well as Mexico and parts of South America. It prefers high elevation to low but is impressively adaptive and can grow well in moist, loose soil with good drainage at almost any elevation and in just about any temperate climate. Once established, amaranth can continue to thrive in low-water conditions, making it especially valuable in sub-Sahara Africa where water sources are few, especially in the dry season. Looking a little closer to home, amaranth received renewed interested as a food source in the United States back in the 1970s. Today, you can find it growing in small amounts in some pretty surprising locations, including Iowa, Nebraska, Missouri, North Dakota, and even Long Island, NY! At present amaranth is grown in the USA, South America, India, China and Russia. The Czech Republic is the most important grower in Europe (Anon.*,* 2015b).

Nutritional Value of Amaranth Grains

Amaranth plant is valued for the positive chemical composition of seed that does not contain gluten. Amaranth is very interesting crop from the point of its high production potential. It grows intensively, photosynthesises faster and effectively, does not suffer from major diseases and is tolerant to various extreme conditions *(Anon.,* 2015a). According to Howard (2013) amaranth is a broad-leafed, bushy plant that grows about 1.8 m tall. It produces a brightly colored flower that can contain up to 60,000 seeds. The seeds are nutritious and can be made into a flour. There are around 60-70 different species of amaranth, and a few of them are native to Mesoamerica. "Obesity is a devastating problem in Mexico," "Amaranth may be part of the solution. It is a whole, healthy food that can be produced locally, and it may create the possibility of change". Amaranth is gluten free and its seeds contain about 30 percent more protein than rice, sorghum, and rye, according to a USDA Forest Service report. It is also relatively high in calcium, iron, potassium, magnesium, and fiber. "Amaranth's amino acid profile is as close to perfect as you can get for a protein source. The plant contains eight essential amino acids and is particularly high in the amino acid lysine, which is largely lacking in corn and wheat. Amaranth has been recommended by the World Health Organization as a well-balanced food and recommended by National Aeronautics and Space Administration **(**NASA**)** for consumption in space missions. The variety of amaranth consumed in Mexico has 16 to 18 percent protein, compared with 14 percent protein in wheat and 9 to 10 percent protein in corn. Some studies have shown that amaranth also contains beneficial omega-3s and may help reduce blood pressure (Howard, 2013). Amaranth contains more than three times the average amount of calcium and is also high in iron, magnesium, phosphorus, and potassium. It is also the only grain documented to contain Vitamin C.

Amaranth seeds have high content of proteins, essential amino acids and minerals. All compounds are usually in following ranges: 14-19 % of protein, 5-8 % of lipids, 62-69 % of starch, 2-3 % of total carbohydrates and 4-5 % of fibre. The seed composition is comparable with seed composition of oat. Amaranth bioavailability of protein reaches 78 %. Seed does not contain gluten causing celiac disease to sensitive individuals. In contrast to cereals amaranth has higher content of amino acids mainly lysine, methionine, treonin and cysteine. Starch is the major part of carbohydrates and starch granules are small (1-3 ľm) easily degradable by alpha-amylases. Amaranth starch is highly stabile during freezing and highly resistant to mechanical stress. Lipid content in amaranth seed ranges from 5 to 8 %. Most of it is placed in embryo as linoleic, oleic and palmitic acid. According to the seed composition amaranth oil is similar to the ones made from cotton or maize but has lower digestibility. Amaranth oil contains about 8 % of squalen, a sterol precursor, used in medicine and cosmetic industry. Content of minerals depends on species, and growing conditions. Amounts of calcium and magnesium are higher than amounts in other cereals. Seeds are a good source of vitamins mainly ascorbic acid and B-complex, and antioxidants alpha-tocopherol and beta- and gamma tocotrienols. Amaranth is used as a food ingredient primarily in bread, pasta, baby's food, instant drinks, *etc*. For such purposes seeds have to undergo various processing technologies - boiling, swelling, flaking, extrusion, puffing, roasting, grinding, sprouting, etc. The most common product is flour, whole amaranth seeds in breads, müsli bars, breakfast food and porridges, pastas and biscuits and cookies. Leaves and stems are interesting vegetable suitable for soups, salads or other meals. As a fodder Amaranth is a valuable nutritious feedstuff with high production ability. It also gives starch, protein concentrates, natural dye, a good source of squalen and antioxidants. It is being intensively tested as one of the interesting energy crop (Anon*.,* 2015a). Squalene is a natural 30-carbon organic comppound originally obtained for commercial purposes primarily from shark liver oil (hence its name), although plant sources (primarily vegetable oils) are now used as well, including amaranth seed, rice bran, wheat germ, and olives. Uncooked amaranth grain by weight is 12% water, 65% carbohydrates (including 7% dietary fiber), 14% protein, and 7% fat (Table 3). A 100-gram reference serving of uncooked amaranth grain provides 1,550 kilojoules (371 kilocalories) of food energy, and is a rich source (20% or more of the Daily Value, DV) of protein, dietary fiber, pantothenic acid, vitamin B6, folate, and several dietary minerals (Table 4). Uncooked amaranth is particularly rich in manganese (159% DV), phosphorus (80% DV), magnesium (70% DV), iron (59% DV), and selenium (34% DV). Amaranth has a high oxalate content (Wikipedia, 2023a).

Table 3. Nutritional value per 100 g of Amaranth grain, uncooked

Energy	1,554 kJ (371 kcal)
Carbohydrates	65.25 g
Starch	57.27 g
Sugars	1.69 g
Dietary fiber	6.7 g
Fat	7.02 g
Saturated	1.459 g
Monounsaturated	1.685 g
Polyunsaturated	2.778 g
Protein	13.56 g
Tryptophan	0.181 g
Threonine	0.558 g
Isoleucine	0.582 g
Leucine	0.879 g
Lysine	0.747 g
Methionine	0.226 g
Cystine	0.191 g
Phenylalanine	0.542 g
Tyrosine	0.329 g
Valine	0.679 g
Arginine	1.060 g
Histidine	0.389 g
Alanine	0.799 g
Aspartic acid	1.261 g
Glutamic acid	2.259 g
Glycine	1.636 g
Proline	0.698 g
Serine	1.148 g
Vitamins	Quantity %DV†
Thiamine (B1)	10% 0.116 mg
Riboflavin (B2)	17% 0.2 mg
Niacin (B3)	6% 0.923 mg
Pantothenic acid (B5)	29% 1.457 mg
Vitamin B6	45% 0.591 mg
Folate (B9)	21% 82 µg
Vitamin C	5% 4.2 mg
Vitamin E	8% 1.19 mg
Minerals	Quantity %DV†
Calcium	16% 159 mg
Iron	59% 7.61 mg
Magnesium	70% 248 mg
Manganese	159% 3.333 mg
Phosphorus	80% 557 mg
Potassium	11% 508 mg
Sodium	0% 4 mg
Zinc	30% 2.87 mg
Other constituents	Quantity
Water	11.3 g
Selenium	18.7 µg

Table 4. Nutritional value per 100 g Amaranth grain, Cooked

Energy	429 kJ (103 kcal)
Carbohydrates	18.7 g
Starch	16.2 g
Dietary fiber	2.1 g
Fat	1.58 g
Protein	3.8 g
Vitamins	Quantity %DV†
Thiamine (B1)	1% 0.015 mg
Riboflavin (B2)	2% 0.022 mg
Niacin (B3)	2% 0.235 mg
Pantothenic acid (B5)	29% 1.457 mg
Vitamin B6	9% 0.113 mg
Folate (B9)	6% 22 µg
Vitamin E	6% 0.88 mg
Minerals	Quantity %DV†
Calcium	5% 47 mg
Iron	16% 2.1 mg
Magnesium	18% 65 mg
Manganese	41% 0.854 mg
Phosphorus	21% 148 mg
Potassium	3% 135 mg
Sodium	0% 6 mg
Zinc	9% 0.86 mg
Other constituents	Quantity
Water	75.2 g
Selenium	5.5 µg

Nutritional Value of Amaranth Leaves

The major attributes of amaranths are their adaptability to a wide range of climatic and soil conditions, superior nutritional quality of grain with high protein (12-19%) and complementary amino acid profiles (lysine 5-7%), easily digestible starch, presence of cholesterol lowering fractions in the seed oil and high carotene (pro-vitamin A) contents in the leaves (Ebert *et al.,* 2011). Amaranth is a highly nutritious leafy vegetable, both in raw and cooked form. Its nutritional value is comparable to spinach, but much higher than cabbage and Chinese cabbage. Amaranth is well adapted to high temperatures in the tropics, while spinach lacks heat tolerance and is not an option for tropical climates. Amaranth is low in saturated fats and sodium; cholesterol is absent. It is a good source of calcium, iron, magnesium, phosphorus, potassium, zinc, copper and manganese. It is a very good source of high quality protein with well-balanced amino acids. Many vitamins are found in high levels in both raw and cooked amaranth leaves and stems: vitamin A, vitamin C, riboflavin (vitamin B2), vitamin B6, folate (vitamin B9) and niacin (vitamin B3). Amaranth also contains betacyanines—amaranthine and isoamaranthine—responsible for the red-violet colors of leaves, stems, flowers and seeds. These pigments dissolve in cooking water, which is poured off. Leaves and stems contain the antinutrients nitrate (mostly in stems) and oxalate at a level similar to other leafy vegetables such as spinach and spinach beet. Consumption of 100-200 g of fresh produce per day is safe. Cooking in water removes the toxic components (Ebert *et al*., 2011).

According to Nath and Swamy (2015) there are a number of different types of amaranth. All are grown during the summer and the rainy season. This is the most common leafy vegetable grown during the summer in India. The leaves and tender stems are rich in protein, minerals and vitamins A and C. Amranth is a common leafy vegetable grown in most parts of India. The fresh, tender leaves and stems give delicious preparation on cooking as in the case of the other fresh leafy vegetables. Cooked similar to spinach or spinach beet, it is a cheap vegetable for the common people and is highly rich in vitamin A and C. Besides having the highest protein contents among leafy vegetables, it also contains carbohydrates, calcium and iron. The vitamin A content in different species varies from 23,000 - 54, 110 IU. The leaves contain 130-173 mg vitamin C, 100-130 mg vitamin B, 4 g protein, 397 mg calcium, 83 mg phosphorus, 25.5 mg iron, 341 mg potassium, 247 mg magnesium and 9200 IU of vitamin A. Whether grown for grain or as leafy vegetables, amaranths are highly nutritious and continue to be studied for their human health benefits. Many studies have explored the chemical composition of amaranth seeds, revealing a superior nutritive balance in protein, vitamins, and minerals, including pro-vitamin A (beta-carotene), vitamin C, vitamin K, iron, zinc, manganese, and calcium, compared with staple cereals and legumes. Seeds are gluten-free and contain starch that is unique for certain food and non-food applications. Amaranth seed oil is a novel raw material with unexplored applications. Interestingly, amaranth oil is reportedly the richest plant-based source of squalene, a valuable compound to cosmetic and pharmaceutical industries (Riggins and Mumm, 2023). All parts of the plant are considered edible, though some may have sharp spines that need to be removed before consumption. Cooking decreases its nutritional value substantially across all nutrients, with only dietary minerals remaining at moderate levels. Cooked amaranth leaves are a rich source of vitamin A, vitamin C, calcium, and manganese, with moderate levels of folate, iron, magnesium, and potassium. Amaranth does not contain gluten (Wikipedia, 2023a).

HEALTH BENEFITS

Amaranth was cultivated by the Aztecs and in other tropical climates, but is now experiencing a resurgence in popularity as a gluten-free protein. Though amaranth is derived from the fruit of a flowering plant, it is often referred to as a grain. Very little research has been conducted on amaranth's beneficial properties, but the studies that have focused on amaranth's role in a healthy diet have revealed three very important reasons to add it to our diet.

i) It's a protein powerhouse: At about 13-14%, it easily trumps the protein content of most other grains. We may hear the protein in amaranth referred to as "complete" because it contains lysine, an amino acid missing or negligible in many grains.

ii) It is good for our heart: Amaranth has shown potential as a cholesterol-lowering whole grain.

iii) It is naturally gluten-free: Gluten is the major protein in many grains and is responsible for the elasticity in dough, allows for leavening, and contributes chewiness to baked products. But more and more people are finding they cannot comfortably – or even safely – eat products containing gluten, often due to Celiac disease. When people with celiac disease eat gluten (a protein found in wheat, rye and barley), their body mounts an immune response that attacks the small intestine. These attacks lead to damage on the villi (small fingerlike projections that line the small intestine) that promote nutrient absorption. When the villi get damaged, nutrients cannot be absorbed properly into the body. It is an autoimmune digestive disease that damages the body's ability to absorb nutrients from food. This makes amaranth an important grain to take note Celiac Awareness (*Anon.,* 2015b).

Mom (2013) reported the following health benefits of Amaranth:

- **Amaranth is gluten-free**. Cook amaranth grain as a hot cereal to eat in the morning. Find it as flour and use if for baking. Some even pop it like popcorn.
- **It has more protein than other grains**. One cup of amaranth grain has 28.1 g of protein compared to oats at 26.1 g. It is healthier to receive protein from plant-based sources rather than animals, because the latter often comes with fat and cholesterol.
- **Amaranth provides essential lysine**. Amaranth has far more lysine, an essential amino acid that the body can't manufacture, than other grains. Lysine helps metabolize fatty acids into energy, absorb calcium, and even keep the hair on our head intact.
- **Helps with hair loss and graying**. Eating amaranth helps with hair loss; juice the leaves and apply it after shampooing. It is said that it helps moisturize and flatten wiry grey hair.
- **Lowers cholesterol and risk of cardiovascular disease**. Amaranth seeds and oil (found in the seed) have fiber which contributes to lower cholesterol and risk of constipation. It is also rich in phytosterols, which are known for lowering cholesterol.
- **It is high in calcium**. Amaranth helps reduce risk of osteoporosis and other calcium deficiencies because it has twice the calcium as milk.
- **Amaranth is full of antioxidants and minerals**. It is the only grain to have vitamin C, but it is high in vitamin E, iron, magnesium, phosphorus and potassium which are necessary for overall health. The leaves are high in vitamin C, vitamin A and folate.
- **Works as an appetite suppressant**. Protein reduces insulin levels in the blood stream and releases a hormone that makes us feel less hungry. Since amaranth is roughly 15% protein, the fact that it aids in weight loss or maintaining weight is one of the health benefits.
- **Improves eyesight**. Some cultures believe that amaranth greens are a natural way to improve eyesight.
- **Amaranth is easy to digest**. Amaranth is traditionally given to patients recovering from illness or people coming off of fasts. It is the mix of amino acids that allows for very easy digestion.

In terms of human health, studies have identified bioactive seed peptides, flavonoids, and other components that may benefit those with hypertension and cardiovascular disease (Riggins and Mumm, 2023)

CULTURAL SIGNIFICANCE

Diego Durán described the festivities for the Aztec god Huitzilopochtli. The Aztec month of Panquetzaliztli (7 December to 26 December) was dedicated to Huitzilopochtli. People decorated their homes and trees with paper flags; ritual races, processions, dances, songs, prayers, and finally human sacrifices were held. This was one of the more important Aztec festivals, and the people prepared for the whole month. They fasted or ate very little; a statue of the god was made out of amaranth seeds and honey, and at the end of the month, it was cut into small pieces so everybody could eat a piece of the god. After the Spanish conquest, cultivation of amaranth was outlawed, while some of the festivities were subsumed into the Christmas celebration. Amaranth is associated with longevity and, poetically, with death and immortality. Amaranth garlands were used in the mourning of Achilles. John Milton's *Paradise Lost* portrays a showy amaranth in the Garden of Eden, "remov'd from Heav'n" when it blossoms because the flowers "shade the fountain of life" He describes amaranth as "immortal" in reference to the flowers that generally do not wither and retain bright reddish tones of color, even when deceased; referred to in one species as "love-lies-bleeding." (Wikipedia, 2023a).

REFERENCES

Ajantaa Pal, Swasti S. Swain, Anath B. Das, Arup K. Mukherjee, and Pradeep K. Chand. 2013. Stable germ line transformation of a leafy vegetable crop amaranth (Amaranthus tricolor L.) mediated by Agrobacterium tumefaciens. In Vitro Cellular & Developmental Biology. Plant, 49 (2): 114-128

Andini, R., Sulaiman, M.I., Kadapi, M., Ohsawa, R. 2021. Polyploidy and Hybridization for Amaranth Crop Improvement. In: Adhikary, D., Deyholos, M.K., Délano-Frier, J.P. (eds) The Amaranth Genome. Compendium of Plant Genomes. Springer, Cham. https://doi.org/10.1007/978-3-030-72365-1_9

Andrea P Castellanos-Arévalo, Andrés A Estrada-Luna, José L Cabrera-Ponce, Eliana Valencia-Lozano, Humberto Herrera-Ubaldo, Stefan de Folter, Alejandro Blanco-Labra, John P Délano-Frier. 2020. Agrobacterium rhizogenes-mediated transformation of grain (*Amaranthus hypochondriacus*) and leafy (*A. hybridus*) amaranths. Plant Cell Rep., 39(9):1143-1160.

Anonymous. 2015a. Amaranth (*Amaranthus* sp. L.). http://www.vurv.cz/ altercrop/amaranth.htm

Anonymous. 2015b. Amaranth - May Grain of the Month.Whole Grains Council. http://wholegrainscouncil.org/whole-grains-101/amaranth-may-grain-of-the-month-0

Arya, I.D., Chakravarty, T.N., and Sopori, S.K. 1993. Development secondary inflorescences and in vitro plantlets from inflorescence cultures of amaranthus paniculatus, plant cell reports, 12, 286, 1993.

Bagga, S., Venkateswarlu, K., and Sopori, S.K. 1987. In vitro regeneration of plants from hypocotyl segments of Amaranthus panuculatus, plant cell reports, 6, 183, 1987.

Bao-Hua, Song., Xue-Jie, Zhang., Fa-Zeng, Li and Peng, Wan. 2002. Chromosome numbers of 14 species in Amaranthus from China. Acta Phytotaxonomica Sinica, 40(5): 428-432.

Bennici, A., Schiff, S., and Bovelli, R. 1992. In vitro culture of species and varieties of four Amaranthus L. apecies, Euphytica 62, 181, 1992.

Binay Panda, Bibha Choudhary, and Subhashini Srinivasan. 2014. The Draft genome and transcriptome of *Amaranthus hypochondriacus*: A C4 dicot producing high-lysine edible pseudo-cereal. DNA Research, pp. 1–18, (July 2014)

Brenner, D.M., Baltensperger, D.D., Kulakow, P.A., Lehmann, J.W., Myers, R.L., Slabbert, M.M. and Sleugh, B.B. 2000. Genetic resources and breeding of *Amaranthus*. Plant BreedingReviews, 19: 227–283.

Bressani, R. 2003. Amaranth-Origin and Distribution. In: Encyclopedia of Food Sciences and Nutrition (Second Edition). 2003.

Broekaret, W.F., Marien, W., Terras, F.R.G., De Bolle, M.F.C., Proost, P., Van Damme, J., Dillen, C.M., Rees, S., Vanderleyden, J., and Cammue, B.P.A. 1992. Antimicrobial peptides from Amaranthus caudatus seedswith sequence homologyto the cysteine/glycine-rich domain of chitinbinding proteins. *J. Biochem.,* 31: 4308

Byrnes, D. R., Dinssa, F. F., Weller, S. C. and Simon, J. E. 2017. Elemental Micronutrient Content and Horticultural Performance of Various Vegetable Amaranth Genotypes. Journal of the American Society for Horticultural Science J. Amer. Soc. Hort. Sci., 142(4), 265-271.

Cai, Y.Z., Corke, H. and Wu, H.X. 2004. Amaranth. In: Encyclopedia of Grain Science. Pp. 1-10. 2004.

Chauhan, Tushar. 2020. Genetically Modified Organisms (GMO)- Definition, Process and Examples. https://geneticeducation.co.in/genetically-modified-organisms-gmo-definition-process-and-examples/

Cheung, A.Y., Bogorad, L., Montagu, M.V., and Schell, J. 1988. Relocating a gene for herbicide tolerance: a chloroplast gene is converted into a nuclear gene, Proc, Natl, Acad, Sci, U.S.A., 85: 391.

Das, S.. 2016. Breeding of Amaranths. In: Amaranthus: A Promising Crop of Future (pp.107-145). https://www.researchgate.net/publication/305520226_Breeding_

Dehmer, A.Y., Graner, A., and Wenzel, G. 1991. Screening for defined DNA sequences in minimal amounts of barley tissue by PCR, plant breed., 107: 70

Delgado, H. and Martín, J.P. 2023. Genetic Diversity of Black Amaranth (Amaranthus quitensis Kunth) Landraces of Ecuadorian Highlands: Association Genotypes—Color Morphotypes. Agriculture, 13(1), 34; https://doi.org/10.3390/agriculture13010034

Dharajiya, D.T., Singh, A.K., Tiwari, K.K., Prajapati, N.N. 2021. Genetic Diversity in Amaranth and Its Close Relatives. In: Adhikary, D., Deyholos, M.K., Délano-Frier, J.P. (eds) The Amaranth Genome. Compendium of Plant Genomes. Springer, Cham. https://doi.org/10.1007/978-3-030-72365-1_6

Eagri. 2023a. Origin, area, production, varieties, package of practices for Amaranthus, Palak And Gogu. www.eagri.org/eagri50/HORT281/pdf/lec31.pdf

Ebert, Andreas W. , Wu, Tien-hor & Wang, San-tai. 2011. Vegetable amaranth (*Amaranthus* L.). International Cooperator's Guide. AVRDC Publication Number: 11-754

Faseela, K.V. and Salikutty Joseph. 2007. Molecular characterization of amaranth landracesand assessment of interspecific relationships among *Amaranthus* spp. (L.) using RAPDmarkers. Indian Journal of Genetics and Plant Breeding, 67: 12–17.

Flores, H.E. and Galston, A.W. 1992. In vitro culture of grain and vegetable amaranth (*Amaranthus* spp.), Am. J. Bol. 69, 1049, 1992.

Fromm, M.E., Taylor, L.P., and Walbot, V. 1986. Stable transformation of maize after gene transfer by electroporation, nature, 319, 791, 1986.

Geri H (1984) Growing Chinese Vegetables in Your Own Backyard. Storey Publishing. Pp 5-10.

Green Deane. 2012. Amaranth, the forgotten food. Amaranth: Grain, Vegetable, Icon. Eat the weeds and other things too. http://www.eattheweeds.com/amaranth-grain-vegetable-icon/

Grimsley, N.H., Ramos, C, Hein, T., and Hohn, B. 1988. Meristematic tissues of maize plants are most susceptible to agroinfection with maize streak virus. Biotechnology, 6: 185

Herrera – Estrella, L. and Simpson, J. 1988. Foreign Gene expression in plants. In: plant molecular Biology. A Practical Approach, Shaw, C.H., ED., IRL Press, Oxford, 1988. 131.

Hibberd, K.A. 1984. Induction, selection and characterization of mutants in maize cell cultures. In cell culture and somatic cell genetics cell plants, Vol. I. Vol.1. Vasil, indra K., Ed., Academic press, New Yprk, 1984, 571.

Howard, Brian Clark. 2013. Amaranth: Another Ancient Wonder Food, But Who Will Eat It?. National Geographic. Published August 12, 2013. http://news.nationalgeographic.com/news/2013/08/130812-amaranth-oaxaca-mexico-obesity-puente-food/?google_editors_picks=true

Jofre-Garfias, A. E., Villegas-Sepúlveda, N., Cabrera-Ponce, J. L., Adame-Alvarez, R. M., Herrera-Estrella, L., and Simpson, J. 1997. Agrobacterium-mediated transformation of Amaranthus hypochondriacus: light- and tissue-specific expression of a pea chlorophyll a/b-binding protein promoter. Plant Cell Reports, 16: 847–852

Jofre-Garfias, A.E., Cabrera-Ponce, J.L., Adame-Alvarez, R.M., Herrera-Estrella, and June Simpson. 2001. Chapter 2: Transgenc

Amaranth (*Amaranthus hypochondriacus*). In: (Edr. YPS Bajaj) Genetic Transformation of Amaranth (Amaranthus hypochondriacus). Springer-Verlag , January 2001, Pp. 13-25

John, H.M, , Dorothy, N., Dorothy, N.N., and Dorothy, M. 2008. Efforts to promote amaranth production and consumption in Uganda to fight malnutrition. In: (Eds. Robertson, G.L. and Lupien, J.R.) Using Food Science and Technology to Improve Nutrition and Promote National Development. International Union of Food Science & Technology.

Kara Rogers. 2020. Genetic engineering. The Editors of Encyclopaedia Britannica. https://www.britannica.com/science/ genetic-engineering

Komen, J. 1992. Grains for the tropical regions, Biotechnology and development Monitor, publication of the Ministry of Foreign Affairs and the University of Amsterdam, The Netherlands, No. 10. March. 1992, 3.

Kuluev, B. R., Mikhaylova, E. V., Taipova, R. M. and Chemeris, A. V. 2017. Changes in phenotype of transgenic amaranth *Amaranthus retroflexus* L., overexpressing *ARGOS-LIKE* gene. Russian Journal of Genetics, 53: 67–75.

Lee, J.R, Hong G.Y, Dixit, A., Chung J.W., Ma, K.H., Lee, J.H., Kang, H.K., Cho, Y.H., Gwag, Gand Park, Y.J. 2008. Characterization of microsatellite loci developed for *Amaranthushypochondriacus*and their cross–amplification in wild species. Conservation Genetics, 9:243–246.

Lee, R.M., Thimmapuram, J., Kate, A., Thinglum, G.G., Hernandez, A.G., Wright, C.L., Kim,R.W., Mikel, M.A. and Tranel, P.J. 2009. Sampling the waterhemp (*Amaranthustuberculatus*) genome using pyrosequencing technology. Weed Science, 57: 463–469.

Madhusoodanan, K.J. and Pal, M. 1981. Cytology of vegetable amaranths. Botanical Journal of the Linnean Society, London, 82: 61-68.

Maestri, Nicoletta. 2015. Amaranth-The Origin and Use of Amaranth in Ancient Mesoamerica. http://archaeology.about.com/ od/amthroughanterms/a/Amaranth.htm

Mallika, V.K. 1987. Genome analysis in the genus amaranthus. PhD thesis, Kerala Agricultural University, Trichur, Kerala.

Mallory, M.A., Rozaura, V., Hall, A.R., McNabb, D.B., Pratt, E., Jellen, N. and Maughan, P.J.2007. Development and characterization of microsatellite markers for the grain amaranths. Crop Science, 48: 1098–1106.

Maughan, P.J., Sisneros, N., Luo, M., Kudrna, D., Ammiraju, J.S and Wing, R.A. 2008.Construction of an amaranth (*Amaranthus hypochondriacus*) bacterial artificial chromosomelibrary and genomic sequencing of herbicide target genes. The Plant Genome, 48: 85–94.

Meeta Sunil1, Arun K. Hariharan, Soumya Nayak, Saurabh Gupta, Suran R. Nambisan, Ravi P. Gupta,

Moghadam, S.H., Alebrahim, M.T., Mohebodini, M., MacGregor, D.R. 2023. Genetic variation of *Amaranthus retroflexus* L. and *Chenopodium album* L. (Amaranthaceae) suggests multiple independent introductions into Iran. Front. Plant Sci., 13. https://doi.org/10.3389/fpls.2022.1024555

Mom, La Jolla. 2013. 10 health benefits of amaranth grain and leaves. In Food and Drink. http://lajollamom.com/amaranth-grain-leaves-health-benefits/

Mosyakin and Robertson. 1996. "New infrageneric taxa and combinations in *Amaranthus* (Amaranthaceae)". Ann. Bot. Fennici, 33: 275–281.

Mosyakin, S.L. and Robertson, K.R. 2003. Amaranthus. In: Flora of North America. North of Mexico. Oxford University Press, New York, USA

Nath, Prem and Swamy, K.R.M. 2015. Vegetables for the Tropical Region (in Press). ICAR, New Delhi. Pp 450.

Nguyen, D.C., Tran, D.S., Tran, T.T.H., Ohsawa, R. and Yoshioka, Y. 2019. Genetic diversity of leafy amaranth (*Amaranthus tricolor* L.) resources in Vietnam. Breed Sci., 69(4):640-650. doi: 10.1270/jsbbs.19050. Epub 2019 Oct 9. PMID: 31988628; PMCID: PMC6977444.

Pal, M. 1999. Amaranthus : Evolution, Genetic Resources and Utilization. *EnviroNews*, 5(4): reproduced from the archives of EnviroNews - Newsletter of ISEB India.

Pal, M. and Khoshoo, T. N. 1973a. Evolution and improvement of cultivated amaranths. VI. Cytogenetic relationships in grain types. Theor. Appl. Gen., 43: 242–251.

Perez de la Vega, M. 1993. Biochemical characterization of populations, in: Plant Breeding: Principles and Prospects, Hayward, M.D., Bosemark, N.O., and Romagosa, L., Eds., Chapman & Hall, London, 1993, 184.

Putnan, Dan. 1992. Amaranth and the currents of history. Legacy, 5(1):1-4.

Queiros, M. 1989. Cytotaxonomic studies of *Amaranthus* in Portugal. *Lazaroa*, 11: 9-17.

Rachael, L. 2018. Amaranth: An ancient grain with impressive health benefits. Healthline Wellness Newsletter, June 2018. https://www.healthline.com/nutrition/amaranth-health-benefits

Raina, A., and Datta, A. 1992. Molecular cloning of a gene encoding a seed-specific protein with nutritionally balanced amino acid composition from Amaranthus. Proc. Natl. Acad. Sci. USA. 89: 11774

Ranade, S.A., Kumar, A., Goswami, M., Farooqui, N. and Sane, Ñ.V. 1997. Genome analysisof amaranths: Determination of inter- and intra-species variations. Journal of Biosciences, 22: 457–464.

Rauh, Amy Lawton. 2003. Research activities: North Carolina State University. http://www.clemson.edu/genbiochem/people/alawton_rauh.php

Ray, T. and Roy, S.C. 2009. Genetic diversity of amaranthus species from the indo–gangeticplains revealed by RAPD analysis leading to the development of ecotype–specific SCARmarker. Journal of Heredity, 100: 338–347

Riggins, C.W. and Mumm, R.H. 2023. Amaranths. https://doi.org/10.1016/j.cub.2021.05.058

Saiki, R.K., Gelfand, H.D., Stoffel, S., Scharf, S.J., Higuchi, R., Horn, G.T., Mullis, K.B., and Erlich, H.A. 1988. Primer-directed enzymaticamplification of DNA with a thermostable DNA polymerase, Science, 239: 487.

Sammour, R.H., Mira, M., Radwan, S.and Fahmey, S.2020. Genetic diversity and phylogenetic relationships among and within Amaranthus spp. using RAPD markers. Revista mexicana de biodiversidad, Volume 91. https://doi.org/10.22201/ ib.20078706e.2020.91.3254

Sammour, R.H., Radwan, S.A. and Mira, M. 2012. Genetic Diversity in Genus Amaranthus: From Morphology to Genomic DNA. BioSciences, 6(11): 351-360

Sanford, J.C. 1990. Biolistic plant transformation, physiol, plantarun, 79, 206, 1990.

Sauer, J. D. 1967. The grain amaranths and their relatives: A revised taxonomic and geographic. Annals of the Missouri Botanical Garden, 54(2): 103-137.

Sauer, J.D. 1955. Revision of dioecious amaranths. Madrono, 13:5-46.

Sauer, J.D. 1957. Recent migration and evolution of the dioecious amaranths. Evolution, 2(1): 11-31. Society for the Study of Evolution. http://www.jstor.org/stable/2405808

Sauer, J.D. 1986. Grain amaranths (Amaranthus spp.— Amaranthaceae). In: (edr. N.W. Simmonds) Evolution of crop plants. Longman Scientific & Technical, England. Pp. 4-7.

Segura-Nieto, M., Rodrigues-Nester, C., and Olguin-Martinez, L. 1992. Identification of methionine rich proteins from Amaranthushypochondriacus seed . Presentd at the Intl. Symp. Biotechnol. Crop Improvement in Latin America (CQI 10), November 1 to 7, 1992.

Shillito, R.D. and Saul, M.W. 1988. Protoplast isolation and transformation, in plant molecular biology, A practical approach, Shaw, C.H., E.D., IRL, press, oxford, 1988, 161.

Shodhganga (2018) General Introduction of Plant. Chapter 1. Shodhganga. shodhganga.inflibnet.ac.in/jspui/bitstream/10603/ 172291/1/chapter%201.pdf

Simpson, M.G. 2010. Diversity and Classification of Flowering Plants: Eudicots. In: Plant Systematics (Second Edition), 2010

Valdes, S., Chagolla, A., Martinez, N., Mendiola, E., Segura, M., and Blanco, A. 1992. Study of a protease inhibitor from amaranth (PO- 171). Presented at the VII PAABS Congress and XIX Congr. Mexican Biochem Soc., Mexico, Sept. 27 to Oct. 2, 1992.

Varalakshmi, B. 2015. Vegetable Amaranth. In: (eds. K.V. Peter and Pranab Hazra) *Handbook of Vegetables* Vol.3. pp 487-520. Studium Press LLC, USA.

Vasil, V. and vasil, I.K. 1984. Induction and maintenance of embryogenic callus cultures of Gramineae, in cell culture and somatic cell genetics of plants, vol. I, Vasil, Indra K., ED., Academic Press, New York, 1984, 36.

Vidhi, J. 2023. Amaranth: Origin, Botany and Varieties | India.

Wang, Joy Y. 2012. Last Chance Foods: Amaranth's Ancient History. http://www.wnyc.org/story/225970-last-chance-foods-amaranths-ancient-history/

WIKI. 2015. Amaranth. From Wikipedia, the free encyclopedia. http://en.wikipedia.org/wiki/Amaranth

WIKI. 2015a. Evolution. From Wikipedia, the free encyclopedia. *http://en.wikipedia.org/wiki/Evolution*

WIKI. 2020. Genetically modified plants. From Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Genetically_modified_plant

Wikipedia. 2023a. Amaranth. From Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Amaranth#:~:text=There%20are%20approximately%2075%20species%20in%20the%20genus%2C,with%20members%20of%20

****