Genetic mechanisms of pigment accumulation in carrot colours

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We hear from Philipp Simon, from the USDA, Agricultural Research Service & University of Wisconsin, Madison, about how a kaleidoscope of colors reveals new genetic mechanisms of pigment accumulation in carrot colors

Most consumers in the Western world today are only familiar with orange carrots, and while orange is the color of most carrots grown globally today, red carrots are widely grown in Asia. Furthermore, the predominant color of carrots was not always orange. In fact, yellow and purple were the original colors of carrots in Central Asia (especially Afghanistan) over 1,000 years ago, where carrots were likely first widely grown as a root crop.

Domestication of carrots generated a vibrant range of colors

But since cultivated carrots were domesticated from wild carrots, let's start with the history of carrot colors with wild carrots, often called Queen Anne's Lace. Wild carrots occur widely around the world today as a weed growing along roadsides and in vacant lots, and

they have white roots, which are edible and taste like carrots, albeit often with a strong carrot flavor. There is no written history documenting the development of the first yellow and purple cultivated carrots, but we deduce that the first domesticators of carrots likely first foraged local wild carrots growing in the countryside of Central Asia, went back to gather seed from more palatable wild populations, and started cultivating that seed where they eventually found that some of those early cultivated carrots were yellow and purple.

Beyond the unrecorded very early domestication history of carrot, written (albeit scant) historical records document yellow and purple carrots in Afghanistan, then Iran and northern Arabia in the 10th century. Carrots were then reported in Syria and Anatolia in the 11th century, north Africa and Spain in the 12th century, Italy in the 13th century, and northern Europe in the 14th century. Early carrots were also carried by traders east of Central Asia to China by the 13th century. With their introduction to Asia, red carrots were developed, becoming a prominent color of Asian carrots.

In addition to written records, works of art have been a valuable resource in documenting the historical record of carrot colors. Early botanical treatises of the Roman Empire, before the common era, depict what may be orange carrots. But it was not until the 14th century that orange carrots are first seen in still life artworks in southern Europe, and by the 1500's, orange carrots became widely developed in northern Europe. With the expansion of global trade in that era, orange became the primary color of carrots grown globally.

Carrot colors deliver diverse nutrients

Jumping forward to the 19th century, organic chemists began characterizing the naturally occurring pigments found in carrots and many other vegetables and fruits. The carotenoid pigments play a very prominent role in carrot colors, with lutein accounting for the color of yellow carrots, alpha- and beta-carotene for orange carrots, and lycopene for red carrots. Anthocyanins account for the color of purple carrots. Modern nutritional scientists have demonstrated that all the carrot pigments are bioavailable. And studies with diverse vegetables and fruits have shown their health benefits, with lutein protecting against age-related macular disease, lycopene protecting against some forms of cancer, and alpha- and beta-carotenes conferring the most significant health benefit as sources of vitamin A, which is an essential nutrient. The anthocyanins and carotenoids also have antioxidant properties, reducing the effects of damaging oxidizing chemicals found in the environment.

Why would carrot roots be so colorful?

Carotenoids play a critical role in photosynthesis by assisting chlorophyll in harvesting the energy of sunlight to convert carbon dioxide and water to glucose and oxygen. They also protect the photosynthetic pigment-protein complexes in leaves from harmful oxidizing by-products of photosynthesis. Both carotenoids and anthocyanins attract animals that

pollinate flowers and disperse the fruit of many plants. So why are there carotenoids and anthocyanins in carrot roots, where no photosynthesis is underway and no reliance on animals to disperse roots?

Apparently, early domesticators of carrots discovered naturally occurring genetic variation in white wild or early cultivated carrots, where lutein and anthocyanins accumulated in carrot roots, and they selected these novel colors over the generations that they grew the crop. So the colors familiar to us in cultivated carrots today are pigments out of place – occurring in roots, rather than their usual occurrence in leaves and fruits.

Recent research reveals novel genetics of pigment accumulation & boosts nutritional value

These pigments of carrots have also drawn the attention of geneticists in the last 75 years. Early studies demonstrated that one gene, referred to as the Y gene, accounts for the shift from the white color of wild carrots to the yellow color found in early cultivated carrots, and the P genes account for a similar shift of root color to purple.

Interestingly, while green leaves in all plants accumulate carotenoids, in most plants, roots do not. But in carrots the Y gene upregulates genes of the photosystem to accumulate carotenoids in carrot roots. Similarly, while some wild carrots have purple color in their leaves, but not their roots, the P genes are transcription factors that activate genes for anthocyanin accumulation not only in carrot leaves, but also in carrots with purple roots.

Recent extensive genetic studies of carrots have also led to the discovery of the Or gene, which stimulates the biogenesis of chromoplasts, the organelles in plant cells that accumulate carotenoid pigments in green leaves and in orange-fleshed fruits like melons, as well as in orange carrots. Additional research is underway to study additional genes that alter the amount and type of pigments in carrot roots.

In parallel with the more fundamental research studying mechanisms of pigment accumulation, plant breeding has been underway to develop new breeding stocks to improve the nutritional value of the crop available to consumers. This effort has resulted in an increase in the average grocery store carrot in the U.S. by ~45% in the last 40 years. Since carrot is a crop with a broad base of genetic diversity, the prospects for continued improvement of nutritional value are promising.

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