Physiology of carrot growth and development

Introduction


- The western type of cultivated carrot is thought to derive from the anthocyanin-containing forms found in Afghanistan.

- The first cultivated carrot types were purple or violet; yellow and, later, orange types were derived from this anthocyanin type by selection.

- Carrot has served as a model plant in plant physiology and more recently in biotechnology.
Vegetative development and growth of carrot

Functions and initiation of storage root

• The major ecological function of the carrot storage root is as a reserve of assimilates for the production of a flowering stem after appropriate stimuli.

• It also forms the route for the translocation of photosynthates from shoot to fibrous roots and for the transport of water and nutrients from fibrous roots to the shoot.

• It may further act as a water reservoir, helping to maintain a constant supply of water to the leaves.
• The storage organ derives mainly from root tissues but, in the mature state, the hypocotyl makes up about one inch of the upper part of the storage organ.

• The secondary growth resulting in the swollen taproot begins with the initiation of the secondary cambium between primary xylem and primary phloem.

• The cambium is formed simultaneously with the first leaves.

• Hole et al. (1984) observed initiation of the cambium at 11 days after sowing and completion of the cambial ring at 20 days after sowing in a controlled environment.

• Under field conditions, initiation and completion of the cambium occurred ten days later.

• Cambial cells divide to form xylem on the inside and phloem on the outside.

• Most of the secondary tissues consist of parenchyma cells, which embed the vessels in xylem and sieve tubes and companion cells in phloem.
• As a consequence of enlargement of the circumference of the root, cells of the cortex and endodermis rupture.

• It is at this time that the orange colour appears in the root. Periderm, arising from meristematic activity in the pericycle, forms the new protective layer. Cell division continues throughout the development of the storage root in the field together with cell expansion.

**Partitioning of assimilates within a plant**

• Partitioning of the carbohydrates between plant parts is often described by the concepts “source” and “sink”.

• Source is a plant part that exports more carbon than it imports, while sink is a plant part that imports more than it exports.

• The ability of an organ to import assimilates, sink strength, is affected by the availability of assimilates and distance to the source and, in particular, by the genetically determined ability of the sink to compete for assimilates.

• During vegetative growth, the storage root is considered as a sink, competing with fibrous roots and shoots for the assimilates produced by photosynthetic plant parts.
The relationship between shoot and root can be simply described by estimating the ratio of their weights.

However, the ratio is often related to plant size and age.

The effect on plant size can be overcome by using the ratio of logarithms of organ weights.

Late maturing carrot cultivars have a high shoot to root ratio.

High root yields tended to be associated with large shoots, and the highest yielding cultivars invested in shoot growth during early development.

Timing of initiation of the storage root did not explain cultivar differences in dry matter distribution.
• The ratios of the growth rates of shoot to storage root before and after storage root initiation were positively correlated with the shoot to root ratio at final harvest 125 days after sowing.

• Fibrous roots may also play a role in the control of partitioning: a cultivar with a larger proportion of storage root at maturity was found to invest more carbohydrates in fibrous roots at the time of storage root initiation.

• Environmental conditions modify the partitioning between shoot and storage root.

• Light affects the shoot to root ratios, but mostly via the effect on plant size.

• Shoot to root ratio increase at higher temperature, which may indicate a true change in partitioning, since the total weight also increased.

• The effect of density, like that of light, is attributed to the modification of photosynthesis and growth with a lower total weight and higher shoot to root ratio at high density or in low light.
Climatic factors affecting total plant and storage root growth

- Storage root growth depends on the assimilate supply from the photosynthetic plant parts.

- Since partitioning to the storage root is more or less dependent on the genotype and total plant weight, storage root growth can be estimated from the total growth.

- The main factors determining the potential crop yield are leaf area, net assimilation rate, length of growing period and utilisable fraction of the biomass (harvest index).

- Leaf area index (LAI, ratio of the total area of the leaves of a crop to the ground area) determines the fraction of interception of light.

- Together with the net assimilation rate, which refers to the rate of dry matter production per unit leaf area, LAI determines the rate of dry matter production per area at a given time.

- The length of the growing period affects the yield by its effects on the duration of photosynthesis.
• Carrot has a slow growth rate in the early part of its vegetative development.

• 40–68% of the final shoot weight but only 17–26% of the final root fresh weight was reached at 2–2.5 months after sowing.

• Therefore, much of the early part of the growing season is used for constructing the growing potential for the later part of the season.

Irradiation

• Irradiation is the primary factor regulating photosynthesis. Scientists studied the effects of different light regimes on the growth of carrot at 20°C and obtained higher plant weights with a longer day and higher photosynthetic photon flux density (PPFD).

• Comparison of light regimes with similar daily light integrals showed that a long photoperiod (16 h, 300 µmol m-2s-1) was more effective than a short photoperiod and high PPFD (8 h, 600 µmol m-2s-1).

• long days and high radiation are particularly favourable during early growth stages.
• carrot responded to decreasing PPFD in a different way from red beet and radish.

• Different light intensities at a constant photoperiod had no clear effect on shoot fresh weight or leaf area in carrot, but the dry weight of shoot and the fresh and dry weights of storage root and fibrous roots were reduced in low light.

• The reduction in storage root dry weight was much smaller in carrot than in red beet and radish.

• at decreasing PPFD, carrot maintains leaf area and shoot fresh weight, and its thus high photosynthetic capacity: storage root growth is not therefore severely limited.

• asymptotic response of carrot yield to high plant density is comparable to the response to low light, and therefore light competition at high densities has little effect on the dry matter distribution in carrot.
**Temperature**

- Temperature affects growth mainly by controlling the rates of chemical reactions, and thus the usage of photosynthetic products.

- Carrot is classified as a cool-season crop, the minimum temperature for growth being 5°C and the optimum temperature 18–25°C.

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**CO2**

- An increase in the concentration of carbon dioxide in air generally enhances photosynthesis and growth.

- Dry matter production of carrot has also been reported to be enhanced by an increased CO2 concentration, especially at high temperatures.

- An increase in CO2 concentration promoted dry matter partitioning to roots at an early growth stage and raised the dry matter content of shoot and root.

- A significant increase in dry weight was found in lettuce, carrot and parsley by increasing CO2 concentration.
Water

- Water supply affects photosynthesis indirectly by inducing the stomata to close when there is a shortage of water.

- This results in a drop in the CO2 concentration in the leaf, which inhibits photosynthesis.

- Carrot is not very sensitive to drought as it has a deep and dense root system. Root system of a carrot plant has a total length of 150–200 m at a depth of 0–50 cm.

- Soil compaction and irrigation increased the length of fibrous roots in the upper 30 cm of the soil profile.

- 3-week period of drought at an early stage, from the 2-true leaf stage onwards, increased the yield, but that drought prior to harvest lowered the yield.

Changes in the quality of carrot during growing season

- The optimal timing of harvest is influenced not only by yield quantity, but also by changes in quality.

- The most important quality attributes for carrot are size, shape, uniformity, colour, texture and internal aspects (sensory quality and nutritional value, especially vitamin A).
**Size, shape and uniformity**

- The size of the individual root increases with growing time and total plant weight and is affected by plant density.

- Root size depends on the purpose for which the carrots will be used, but uniformity of size is a common demand.

- Root shape is primarily determined by genotype but it changes during growth and can be modified by environmental conditions.

- Low temperature (10–15°C) and a low soil moisture content increase the root length relative to width.

- Rounding of the root tips together with simultaneous thickening and colouring was defined as ripening (or maturation) of the fleshy root by Banga and de Bruyn (1968).

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**Carbohydrates**

- Soluble sugars are the main form of storage compounds in carrot.

- They account for 34–70% of the dry weight of the storage root and are stored in the vacuoles of the parenchyma cells. Steingröver (1983) divided the development of carrot into three periods:

  - period 1 (18–25 days after sowing at a constant temperature of 20°C), when no soluble sugars are stored

  - period 2 (25–32 days after sowing), when reducing sugars are stored; and

  - period 3, when mainly sucrose is stored in the tap root. At 30–50 days after sowing,

  - the concentration of sucrose starts to increase more rapidly than does that of hexoses (fructose, glucose), resulting in a higher sucrose to hexose ratio.
- A sugar is classified as a reducing sugar only if it has an open-chain form with an aldehyde group or a free hemiacetal group.

- **Monosaccharides** which contain an aldehyde group are known as **aldoses**, and those with a ketone group are known as **ketoses**.

- Reducing monosaccharides include **glucose**, **glyceraldehyde** and **galactose**.

- Many **disaccharides**, like **lactose** and **maltose**, also have a reducing form, as one of the two units may have an open-chain form with an aldehyde group.

- However, **sucrose** and **trehalose**, in which the **anomeric carbons** of the two units are linked together, are non-reducing and neither of the rings is capable of opening.

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Equilibrium between cyclic and open-chain form in one ring of maltose
• Therefore, sucrose is the predominant transport and storage sugar at maturity but its proportion is affected by genotype and environment.

• Cultivars with high net assimilation rates have a capacity for high sugar yield.

• The concentration of starch in carrot storage roots is low, ranging from 1% to 10% of dry matter.

• Changes in the accumulation of reducing and non-reducing sugars have been related to the activities of enzymes, e.g. acid and alkaline invertases and sucrose synthetase.

• Although enzyme activities have not always shown a clear relationship with changes in carbohydrates.
Carotenes and colour

• Carotenes give carrot its characteristic orange colour. There is a positive correlation between carotene content and colour.

• Alfa and beta carotene account for more than 90% of all carotenoids in carrot.

• A high growing temperature is known to favour carotene production.

• Carrots grown in more southerly locations contained a higher level of carotenes than carrots from northern growing sites.

• Carotene content increases with the age and size of the root. In various studies, the maximum content was reached at 90–130 days after sowing.

• The carotene level was clearly reduced when sowing was delayed.
Sensory quality

• Sensory quality is an increasingly important quality aspect.

• non-volatile chemical constituents (sugars and amino acids) are primarily responsible for the taste of fresh carrot and that the contribution of volatile components is small compared with that of nonvolatile compounds.

• high sugar to terpinolene ratios were associated with fresh carrot flavour, aroma, aftertaste and sweet taste.

• the sweetest carrots, which were grown at low temperatures, contained the highest amounts of glucose and fructose and lower amounts of sucrose and total sugars.

• low growing temperature favoured sweet taste, acidic taste, crispness and juiciness of carrots, whereas high growing temperatures resulted in bitter taste and high firmness of roots grown in phytotrons.

• Different day and night temperatures did not alter the sensory quality in comparison to a constant temperature with the same mean temperature.
• total essential oil content remained relatively constant for the first 20 weeks of the growing season but that the concentrations of individual compounds changed.

• At the end of the growing season, the total content of essential oils increased.

• Likewise, concentrations of acetaldehyde and ethanol increased dramatically towards the end of the season, indicating anaerobic respiration.

Compositional changes as indicators of maturity

• According to Watada et al. (1984), physiological maturity, although not usually observed in organs like roots, foliage, stems and tubers, is the stage of development at which a plant or plant part will continue ontogeny, even if detached.

• They distinguish physiological maturity from “horticultural maturity”, the stage of development at which a plant or a plant part can be used for a particular purpose.

• In carrot, maturity in this sense would require a satisfactory outer, sensory and nutritional quality combined with an adequate potential for storage and shelf life.
Several scientists have attempted to find indicators for maturity to optimise the harvest time of carrot with regard to either nutritional values, yield or storage potential.

Sugar content or composition has often been interpreted as a maturity index.

Goris (1969b) and Phan and Hsu (1973) defined maturity as the time at which the concentration of soluble sugars attains a constant value but the root is still growing.

Fritz and Weichmann (1979) suggested use of the sucrose to hexose ratio as the criterion of the appropriate harvest date from the standpoint of nutritional quality but not of storage ability.

Later, Le Dily et al. (1993) monitored compositional changes in carrot overwintering in the field and defined maturity as the stage with the maximum sucrose to hexose ratio.

Rosenfeld (1998) noted that neither the ratio of sugars nor any other chemical variable indicated the presence of a definable stage of biological development that could be considered as maturity.

He concluded that the computed term “cylindricity”, indicating root shape, might be used as a criterion for fully developed roots, together with root weight.