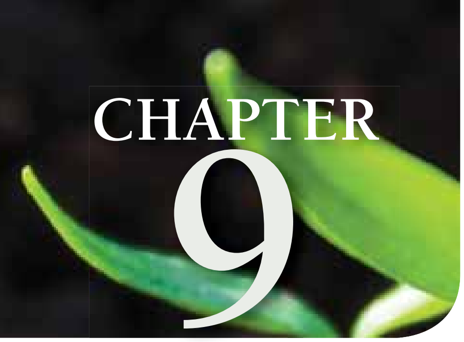

CHAPTER 9 Plant Growth and Development

Chapter Outcomes

After studying this chapter, you will be able to:

- Identify the stages and products of photosynthesis.
- Discuss the function of respiration and recognize the steps.
- Describe the process of transpiration and the effects of different environmental conditions.
- Recall the movement of solutes through the plant.
- Identify the processes of plant reproduction.
- Describe basic plant breeding principles and reasons plant breeding is important.
- Describe the careers for plant physiologists and plant breeders.

Words to Know

adenosine triphosphate (ATP)	genes	phenotype
alleles	genome	photosynthesis
carbon fixation	genotype	plasmalemma
carotenoid	glycolysis	pyruvate
Casparian strip	grana	recessive
chimera	haploid	relative humidity (RH)
chlorophyll	homozygous	respiration
chromatin	incomplete dominance	sport
chromosome	meiosis	stroma
cohesion	mitosis	thylakoid
cytokinesis	mutation	translocation
diploid	nicotinamide adenine dinucleotide phosphate (NADPH)	transpiration
dominant		turgor
fertilization		zygote

Before You Read

Arrange a study session to read the chapter aloud with a classmate. At the end of each section, discuss any words you do not know. Take notes of words you would like to discuss in class.





While studying this chapter, look for the activity icon to:

- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with the Corner Questions and interactive activities.
- **Reinforce** what you learn by completing the end-of-chapter questions.

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The journey to push roots into the soil and stretch leaves towards the sun begins with a tiny seed. Important plant processes are occurring in each plant cell that drive growth and development, enabling a simple seed to mature into an adult plant. These plant processes are basic biological functions. They are responsible for everything from the growth of a giant sequoia to the production of nectar in honeysuckle. The vital processes for this to occur include photosynthesis, respiration, transpiration, translocation, and reproduction. This chapter explains how plants develop and the ways horticulturists can use this knowledge to influence plant growth.

Photosynthesis

Photosynthesis is a process in which plants capture energy from the sun to convert simple molecules of carbon dioxide (CO_2) and water (H_2O) into carbohydrate molecules that can be used by plants as sources of energy and building blocks for other molecules, **Figure 9-1**. Photosynthesis is one of the most important chemical reactions on earth. Photosynthesis is the pathway by which nearly all of the energy in our lives is ultimately derived and through which oxygen is released. Photosynthesis begins with two reactants:

- Carbon dioxide from the air, which enters through the stomata of the leaves.
- Water, which travels to the leaf through the xylem.

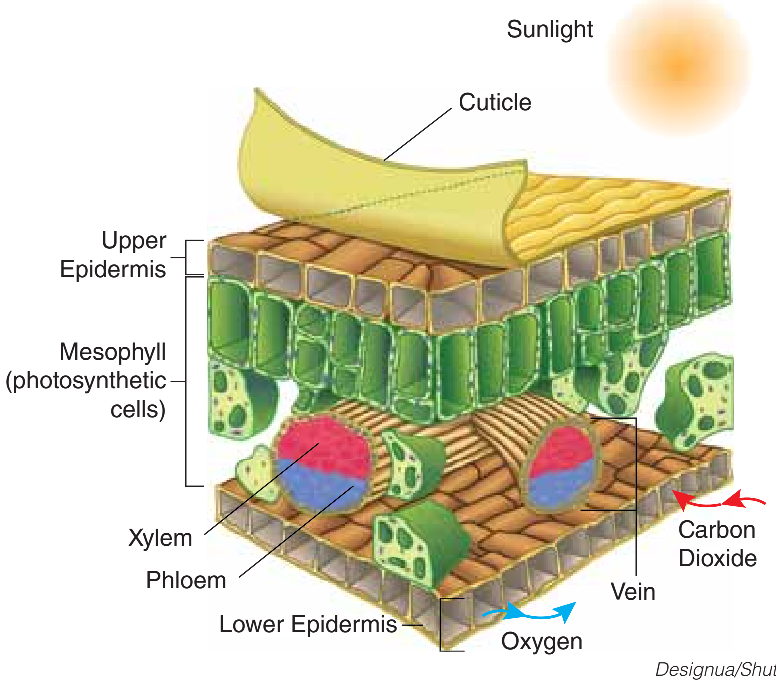

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Figure 9-1. Energy from light drives the process of photosynthesis, converting carbon dioxide and water into sugars used for plant growth and development. Notice that carbon dioxide enters the leaf through the stomata as water leaves the same way.

Oxygen is produced as a by-product of the chemical reaction of photosynthesis. The simplified equation of photosynthesis is:

$$6CO_2 + 6H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2$$

Photosynthesis primarily occurs within the chloroplasts inside plant cells. The chloroplasts have double membranes (like mitochondria). Chloroplasts contain ***chlorophyll***, a pigment that is important in capturing light energy. Chlorophyll is found inside a ***thylakoid***, a disc-shaped sac surrounded by membranes on which the light reactions of photosynthesis take place. Thylakoids tend to be arranged in stacks known as ***grana***. The aqueous space outside of the grana is called the ***stroma***. Both the grana and stroma provide important spaces for parts of the photosynthetic process to occur.

For light energy to be used by plants, it must be first be absorbed by a pigment. Within the chloroplast, these pigments include chlorophyll and carotenoids. Chlorophyll, the principal pigment of the plant that makes leaves appear green, absorbs light primarily in the violet and blue wavelengths and also in the red. Chlorophyll does not absorb green light. Instead, it reflects it and, therefore, makes leaves appear green. This is because there is more chlorophyll in leaves, and it often masks the red-orange ***carotenoid*** pigments. There are two types of chlorophyll: chlorophyll *a* and chlorophyll *b*. **Figure 9-2** illustrates the part of the light spectrum used by plants for photosynthesis. Note that different chlorophyll and other pigments absorb different wavelengths of light, enabling plants to absorb a greater range of light energy.

Light-Dependent Reaction

The process of photosynthesis can be divided into two parts: light-dependent reaction and light-independent reactions. The light-dependent reaction, as the name indicates, occurs in response to light energy being absorbed by chlorophyll. It occurs within the grana, or stacks of thylakoid, within the chloroplasts. Light-independent reaction (discussed in the following section) occurs in the stroma. In the light-dependent process, light energy is converted to chemical energy (sugar).

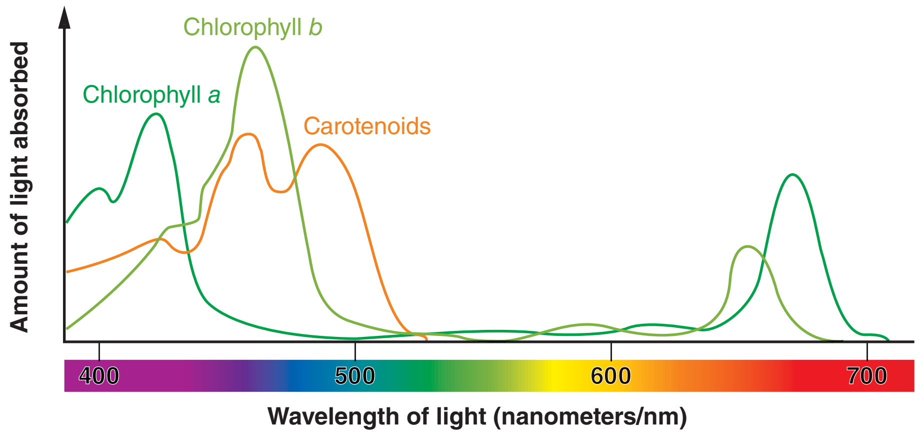

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Figure 9-2. Chlorophyll *a* is the principal pigment responsible for capturing light energy. Chlorophyll *b* and accessory carotenoid pigments extend the range for capturing light.

Corner Question

What do you call sugar that is produced in the process of photosynthesis?

As multiple chlorophyll and other pigment molecules absorb particles of light (photons), the light energy causes electrons to enter an excited state or have a short boost of high energy. These energized electrons move from the chlorophyll molecules to specialized molecules in the thylakoid membrane. In a complex series of reactions, the energy from the excited electrons are passed along an electron transport chain, like a bucket brigade, which is used to create ***adenosine triphosphate (ATP)*** and ***nicotinamide adenine dinucleotide phosphate (NADPH)*** molecules. ATP is a nucleotide found in the mitochondria and the principal source of energy for cellular reactions. The NADPH molecule acts as a carrier for electrons in photosynthesis. These molecules provide energy used in light-independent reactions to make sugar.

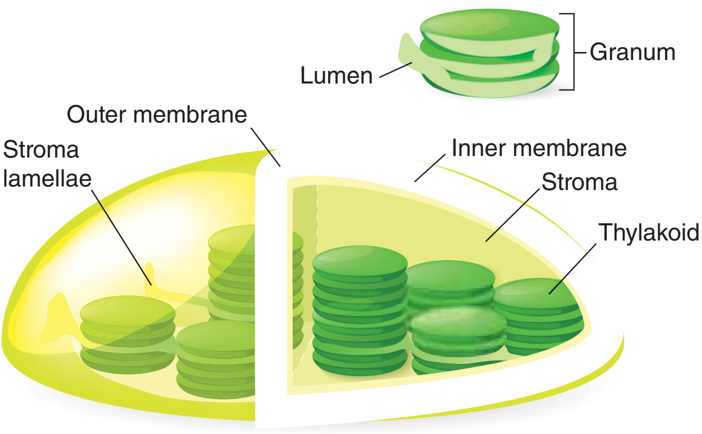

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Figure 9-3. The light reaction occurs within the stacks of thylakoid membranes called the grana.

The excited electrons that leave the chlorophyll molecules are replaced by electrons that come from water molecules, which have been split by an enzyme in the thylakoid. When the water molecules are split, chlorophyll molecules take the electron from the hydrogen atoms, leaving H^+ ions. The remaining oxygen atoms from the divided water molecules combine to form oxygen gas (O_2) and are released from the plant. **Figure 9-3** illustrates the process of the light reaction. Note where the processes occur in the cell and the compounds that are used and produced as part of this reaction.

Light-Independent Reactions

In the last stage of photosynthesis, carbon atoms from carbon dioxide are used to make organic compounds in which chemical energy is stored. This process is called ***carbon fixation***. Carbon fixation principally occurs through a process in the stroma called the Calvin cycle. The Calvin cycle produces a sugar molecule called glucose through a series of chemical reactions assisted by enzymes. ATP and NADPH provide the energy to drive this process. The Calvin cycle begins with molecules of carbon dioxide obtained from the atmosphere through stomata in the leaves. In a series of phases, six carbon dioxide molecules are enzymatically “fixed” (chemically bonded) to another compound. Through the energy of ATP and NADPH, two three-carbon molecules are created that the plant can use to form sugars, starches, and other compounds, **Figure 9-4**. Most plants species fix carbon this way and are called C3 plants, for the three-carbon molecule that is created.

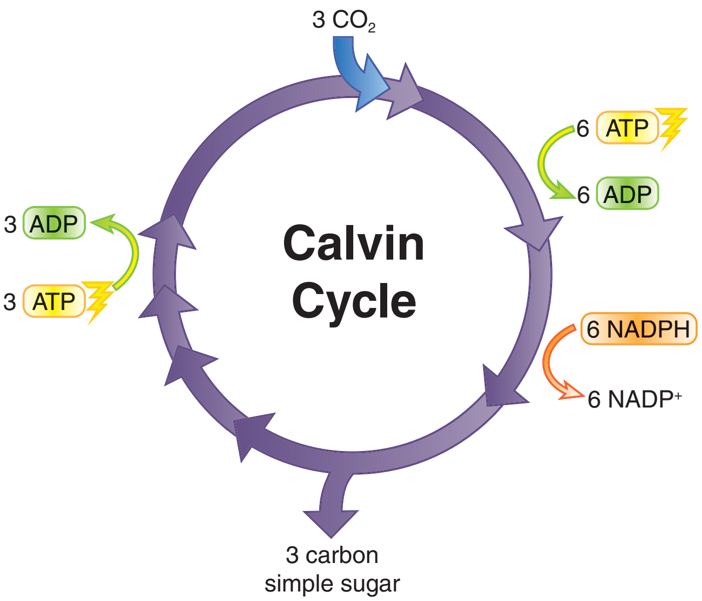

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Figure 9-4. Through a series of reactions, the Calvin cycle yields glucose.

STEM Connection Increase in CO_2 Levels May Increase Plant Production

Researchers estimate that in the year 2050, carbon dioxide (CO_2) levels will be elevated from current levels. The leaves of soybeans grown at these elevated CO_2 levels will photosynthesize and respire more than those grown under current atmospheric conditions. This finding could point to increased crop yields as CO_2 levels rise. The study done by researchers at the University of Illinois and the United States Department of Agriculture found 90 different genes that control respiration were switched on, or expressed, at higher levels in the soybeans grown at high CO_2 levels. This allows the plants to use the increased supply of sugars (from the higher rates of photosynthesis that occur under high CO_2 conditions) to produce energy. The rate of respiration increases significantly (allowing more energy and plant growth) at elevated CO_2 levels.

When stomata remain open to accumulate carbon dioxide, the plant is also losing water through a process called *transpiration*. Under drought conditions, a plant will close its stomata to reduce water loss, resulting in a major decline in photosynthesis. This makes the Calvin cycle an inefficient system because it begins using oxygen in place of carbon dioxide, resulting in no sugars for the plant. Some species of plants that have evolved in drier climates have adapted their carbon-fixation pathways to conserve water without affecting the rate of photosynthesis.

Crassulacean Acid Metabolism (CAM) and C4 Plants

Plants with alternative photosynthetic mechanisms are called C4 plants or crassulacean acid metabolism (CAM) plants, depending upon their carbon-fixation path. The C4 mechanism is found in tropical grasses such as corn, sugarcane, sorghum, or warm-season turfgrasses. C4 plants thrive in high light, high temperatures, and dry conditions. Their leaves concentrate carbon dioxide in particular areas. As a molecule of carbon dioxide enters the leaf, it is temporarily attached to a three-carbon molecule (making a four-carbon molecule, hence the C4 name). The carbon dioxide molecule is shuttled to where it can be used more efficiently, allowing C4 plants to minimize water loss by keeping their stomata closed more often than typical C3 plants.

Many succulents, including cacti and stonecrop, use a crassulacean acid metabolism (CAM) pathway to fix carbon dioxide. (This alternative photosynthetic mechanism was first discovered in *Crassula* species.) Like C4 plants, CAM plants attach a molecule of carbon dioxide to a three-carbon molecule, but they open their stomata at night to minimize water loss. The carbon dioxide molecule is released from the temporary four-carbon molecule during the day so that photosynthesis may resume. Pineapples, Spanish moss, and some orchids are examples of nonsucculent CAM plants, **Figure 9-5**.

In review, photosynthesis is a vital process. It takes carbon dioxide (from the atmosphere) and water and uses energy from light to produce carbohydrates for plant growth. It also processes and releases oxygen as a by-product.

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Figure 9-5. CAM plants such as cacti can often be found in desert conditions.

Respiration

Take a deep breath and fill your lungs with oxygen. Humans and plants both use stored energy to fuel everyday processes. ***Respiration*** is a process in which glucose (the product of photosynthesis) combines with oxygen to produce energy in a form that can be used by plants. Plants take in oxygen and use its electrons to power a series of chemical reactions that creates energy for cells to function.

The sugars produced through photosynthesis are used for processes such as plant growth, flower formation, and fruit development. Sugars can be transported and stored throughout the plant, then converted to energy to power the cellular processes that result in new leaves unfolding, roots pushing deeper into the soil, or seeds forming, among other normal functions. A summary equation for respiration is:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

$$\text{glucose} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

Respiration happens within the mitochondria of plants, and is basically the reverse of photosynthesis. The respiration process yields energy in the form of ATP. ATP (adenosine *tri*phosphate) provides the energy used for plant growth and development functions when the bond between the second and third phosphate in ATP is broken (converting ATP into adenosine *di*phosphate, or ADP). That release of phosphate provides the energy to keep organisms of all types alive. But plants do not make ATP during photosynthesis; they make glucose. Glucose is needed in order to convert ADP back into ATP so that energy will be available for the plant's use when needed.

ATP Production

To make ATP, a glucose molecule is split into two molecules of a compound called ***pyruvate*** through a step called ***glycolysis*** (*glyco* = sugar, *lysis* = splitting). Glycolysis happens in the cell cytoplasm (outside the mitochondria) and produces a small amount of ATP (two ATP molecules). The pyruvate then moves into another series of reactions within the mitochondria called the Kreb's cycle, which in the presence of oxygen produces more ATP. In the third step of respiration, on the inner membrane of the mitochondria, a cycle of reactions called the electron transport system generates more ATP by oxidizing molecules from the earlier reactions in respiration. This is a very broad overview of a very complex process that results in the production of 36 ATP molecules for each glucose molecule, **Figure 9-6**. ATP is sometimes called the currency of the cell, because it provides the energy to drive all cell processes.

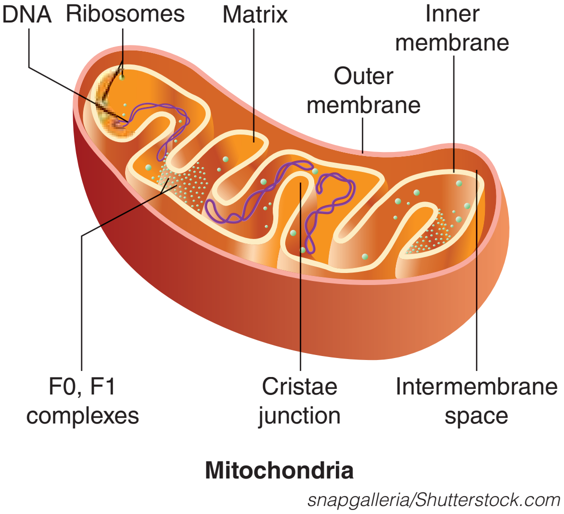

Figure 9-6. Respiration occurs in the mitochondria and produces energy that powers all plant growth and development.

Oxygen is a key ingredient in respiration, which can be problematic for plants growing in water-saturated conditions. These conditions can occur through overwatering or in soils with naturally poor drainage. Water replaces air in the soil pore spaces, leaving plant roots with no oxygen to take up and use in the glucose conversion process. As a result, waterlogged soils that are depleted of oxygen can kill root tissues and reduce plant growth or even result in plant death.

Rates of respiration influence plant growth and are linked to temperature. Raising temperatures can increase growth rates and lowering temperatures can reduce growth rates. Growers need to know the effects of temperature on each crop, as the effects vary by plant species. For example, lilies are very responsive to temperature management. However, temperature has little effect on chrysanthemums.

Corner Question

What is anaerobic respiration?

Transpiration

Have you ever wondered how water travels to the top of a tall tree? Recall that leaves have tiny holes called stomata. When the stomata are open, water vapor is released (much like you lose water when you exhale, which is evident on cold winter days). Water is pulled up through the plant as adjoining water molecules exit the stomata of the plant due to evaporation. Roots take in water as a liquid form through the process of diffusion. Water is then drawn upward through xylem cells and released into the air in a gaseous state. This process is called ***transpiration***. As much as 90%–99% of water that is taken in by roots is lost through transpiration. Water molecules have a property called ***cohesion*** in which hydrogen bonding between adjacent water molecules allows the water to be pulled through the plant, **Figure 9-7**.

"Gardening requires lots of water—most of it in the form of perspiration."
—Lou Erickson

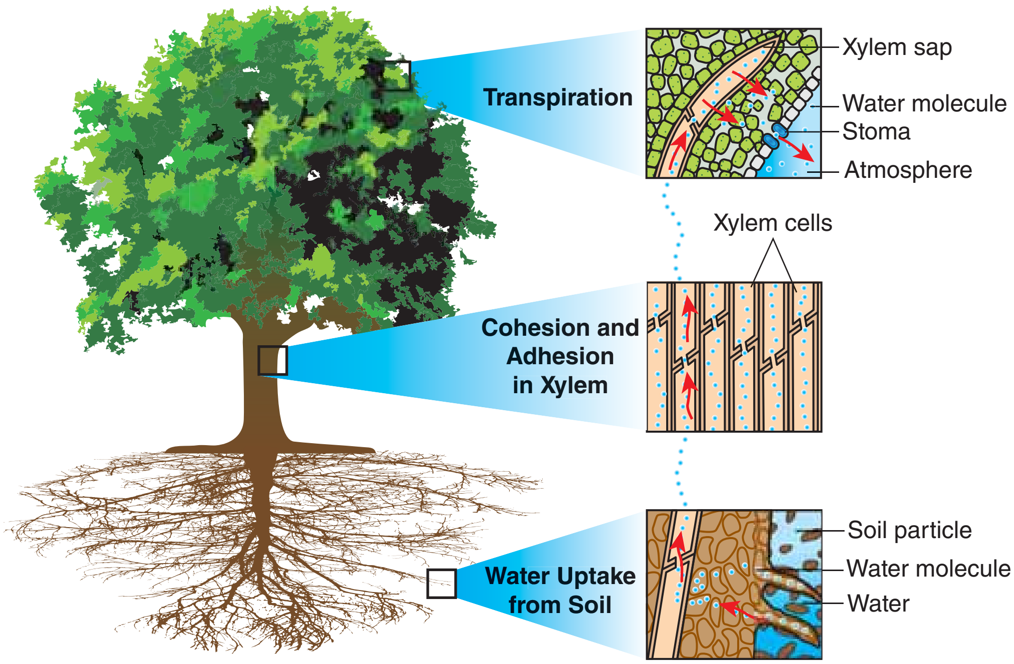

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Figure 9-7. The cohesive properties of water allow it to be drawn upward through the plant from the roots to the leaves.

Transpiration provides these key benefits to plants:

- Carbon dioxide entry.
- Water uptake.
- Nutrient access.
- Evaporative cooling.

Carbon Dioxide Entry

Carbon dioxide is needed for photosynthesis. Carbon dioxide molecules enter the plant through the stomata by diffusion. However, carbon dioxide must enter the leaf through a solution in order to pass through the plasma membrane. To do this, carbon dioxide in its gaseous form must come into contact with a moist cell surface. The water from transpiration provides enough moisture for this process to happen. However, any time water encounters conditions where air is unsaturated evaporation occurs, and water is lost from the plant. This is also called *evapotranspiration*. Plant scientists for this reason have called transpiration a "necessary evil."

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Figure 9-8. Turgor pressure keeps plant cells rigid. If there is a drop in turgor, wilting occurs.

Water Uptake and Nutrient Access

Transpiration drives the process of water uptake in plants. Water serves numerous functions within the plant, including turgor, or cell rigidity. ***Turgor*** is the water pressure within a plant cell that helps provide rigidity and support to plant structures. Water fills vacuoles within plant cells and causes the cell membrane to push up to the cell wall, helping the plant tissues stay rigid. If a plant experiences excessive water loss, plant cells lose turgor, become flaccid, and wilt, **Figure 9-8**. This is why grocery stores use misters to spray produce: it keeps the produce from wilting. Water is necessary for biochemical processes and is a medium for dissolved nutrients. Once nutrients enter the transpiration stream, water carries dissolved inorganic nutrients throughout the plant.

Factors Affecting Transpiration

Transpiration rates are affected by various environmental factors:

- Relative humidity.
- Temperature.
- Water.
- Wind.
- Plant structures.

Relative Humidity

Have you ever experienced a summer day where the air is "sticky"? In some areas of the United States, high humidity levels are common. Humidity, or the stickiness in the air, refers to the level of moisture or water vapor present in the air. On rainy days, the humidity levels are near 100%. In plants, relative humidity becomes important when understanding transpiration rates, water loss, and other issues, such as managing diseases and plant propagation.

Relative humidity (RH) is the amount of water vapor in the air compared to the amount of water vapor that air could hold at a given temperature. The higher the temperature, the greater amounts of water vapor the air can hold. The environment inside a leaf often has a relative humidity near 100%. Water exits the leaf through the stomata when the relative humidity in the atmosphere is less than 100%. The different levels of relative humidity (environment versus inside the leaf) create a gradient that allows the diffusion of water from the leaf into the air. Diffusion is movement of a substance from an area of higher concentration to an area of lower concentration. If there is less moisture in the air, the relative humidity is low, resulting in higher rates of transpiration, **Figure 9-9**. Higher levels of relative humidity mean that there is more water vapor in the air and transpiration rates will be lower.

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Figure 9-9. The hairy leaves of lamb's ear create a thick boundary layer around the leaves and minimize water loss.

Temperature

Increases in temperature will increase rates of transpiration. As temperatures rise, air can hold more water, so relative humidity decreases. The lower relative humidity, combined with an increase in temperature, will speed up the amount of water leaving the plant. To see this process in action, try this: On a sunny, warm day, tie a plastic bag tightly around the leaves at the end of a leafy branch or twig on a tree. A few hours later, return and see how much water has accumulated in the plastic bag.

Water

Plants are constantly pulling water from the soil. Water enters the roots of a plant through diffusion. When more water is in the soil than in the plant, water will enter the plant roots. When water needs of the plant exceed the amount of water available in the soil, turgor pressure in the plant will drop and the stomata will close to prevent more water loss. A plant may recover from wilting when the water uptake catches up with transpiration.

Wind

Air movement across the leaf surface reduces a thin layer of water vapor that surrounds the leaf, called the boundary layer. The boundary layer maintains high levels of relative humidity around the leaf to slow water loss to the environment. When wind blows across the leaf, the boundary layer is reduced, creating a situation where transpiration can increase.

Physical Structures

Physical structures of a leaf may also influence transpiration rates. Some plants have thick, succulent leaves, whereas others are covered with "hairs," called *trichomes*. Plants with trichomes will have larger boundary layers. The trichomes provide a structural barrier that decreases the movement of air, allowing for an accumulation of water vapor that will reduce rates of transpiration.

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Figure 9-10. The waxy surface of a kale leaf slows the loss of water.

Leaves with waxy cuticles are hydrophobic, or water repellent, and can slow water movement from inside the leaf to the atmosphere, **Figure 9-10**. Many desert plants have this feature.

Movement of Solutes

Transpiration is the driving force for moving water throughout the plant. The water stream provides a vehicle for transport of inorganic nutrient ions from the soil through the xylem. Sugars produced during photosynthesis move throughout the plant using a different conduit called the phloem.

Active Uptake of Inorganic Nutrients

Nutrients used by plants are the charged forms (ions) of the elements. Ions can have different charges and different forms. Most of the nutrient ions in the soil are surrounded by water, and can travel with water through the epidermis of the plant and through the cortex. Until water and ions get to the endodermis, the innermost level of the cortex, they can travel *between* cells rather than *through* cells. At the edge of the endodermis, however, is a waxy barrier called the ***Casparian strip***, **Figure 9-11**. Neither water nor ions can pass through this layer without going through the plasma membrane, or ***plasmalemma***. The plasma membrane is permeable to water, but impermeable to ions because of their charges (the interior of the plasma membrane is neutral and repels charges). To get ions into the endodermis and then to the xylem, nutrient ions must be drawn across the plasmalemma using active transport through channels. The plant must use ATP produced during respiration to move the ions into the endodermis, where they can once again travel with the water molecules, this time in the xylem. The transpiration stream moves the water and nutrients throughout the plant.

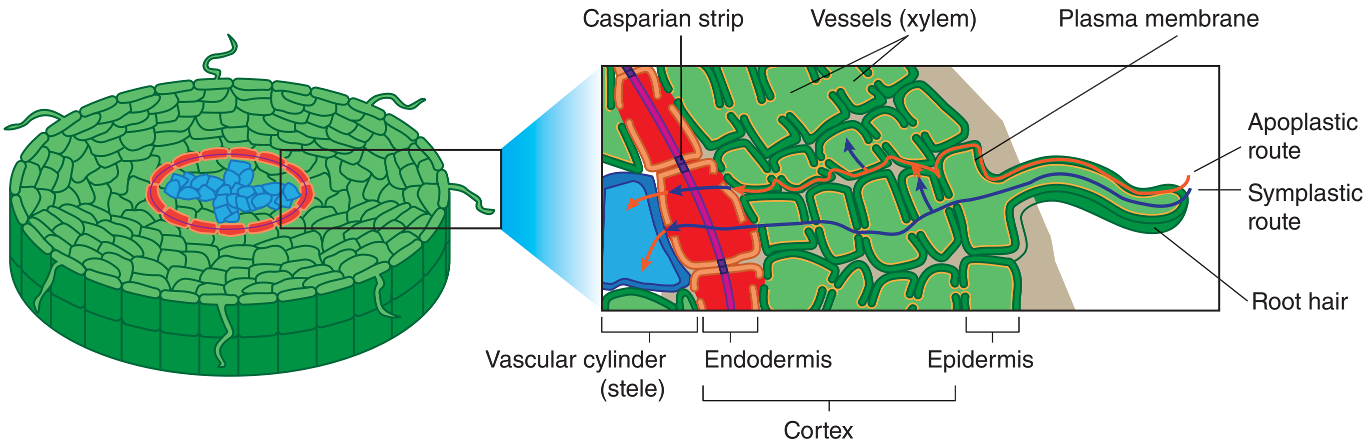

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Figure 9-11. Water travels freely into the root until it encounters the waxy Casparian strip. Water and nutrients must be actively transported across a permeable membrane to enter the plant.

Translocation of Sugars through Phloem

Sugars produced through photosynthesis travel through phloem to parts of the plant needing energy, such as growing tips of shoots and leaves and storage organs in roots, leaves, fruits, and seeds. ***Translocation*** (movement of sugars within the plant) occurs when the *sources* (where sugar is produced or stored in a plant) export sugars to the *sinks* (where sugar is used in a plant). The source can be any photosynthetic tissue, like a leaf, that manufactures sugars, or an organ that has stored sugars, **Figure 9-12**. The sink is any plant tissue that has a need for carbohydrates. Developing fruit is a very competitive sink, as are roots that serve as storage organs, **Figure 9-13**.

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Figure 9-12. Leaves and some stems are the principal producers of sugars and are considered sources.

Ryhor Bruyeu/iStock/Thinkstock

Figure 9-13. A sink is a location in a plant that requires sugars. Fruit is a common sink.

Reproduction

Plant reproduction offers the opportunity to breed better crops that have specific advantages. Plants can be bred or selected to have a number of characteristics that include:

- Higher yields.
- Disease and pest resistance.
- Improved vigor.
- Increased nutritional content.
- Ornamental aesthetics.
- Enhanced stress tolerance.
- Postharvest longevity.

Higher yields mean an increase in harvested products. High yields, together with best production practices, allow for greater profits for growers and more food for the world. Pests and diseases constantly threaten crops. Through plant breeding, cultivars can be produced that allow the plant to use innate resistance to attack, providing a control method for pest management. Plants with strong vigor tend to outcompete other organisms for light, nutrients, and water. An example of vigor is a squash that rapidly leafs out, creating a canopy that shades out weed competition, **Figure 9-14**. Ornamental breeding results in plants with an astonishing variety of leaf colors, shapes, and textures that appeal to

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Figure 9-14. Plants that can rapidly leaf out, such as this zucchini plant, have a competitive advantage against weeds. This is a trait that is selected by breeders. Can you identify any other plants that leaf out rapidly?

V.J. Matthew/Shutterstock.com

Figure 9-15. Note the color variations on this geranium plant. Ornamental breeding creates new, novel plants for home gardeners.

gardeners, and offers growers a unique commodity, **Figure 9-15**. Increasing the nutritional content in plants results in higher levels of nutrients and minerals available for consumers in the foods they eat. For example, breeders might decide to increase beta-carotene levels in sweet potatoes to impact eye health. Some breeding efforts have improved the shelf life of crops with little loss of quality, increasing postharvest longevity. Understanding plant reproduction and genetics enhances knowledge of how new plants can grow and develop.

Cellular Division

Cells reproduce through a process known as cell division, in which a cell and all of the material contained within it splits into two daughter cells. In multicelled organisms, such as plants and animals, cellular division and enlargement allows for growth, repair, or replacement of wounded or dead cells. Each new daughter cell is exactly the same as its parent cell, inheriting an exact replica of all the genetic information. Vegetative, or asexual, propagation of horticultural crops is possible due to a plant's ability to divide its cells. A vegetative cutting from a plant is therefore genetically identical to the plant it was taken from.

Mitosis and Cytokinesis

Asexual reproduction in plants occurs through a process called ***mitosis***. Mitosis is the steps a cell undertakes to duplicate and divide a complete set of chromosomes. Mitosis occurs in four stages: prophase, metaphase, anaphase, and telophase, **Figure 9-16**. In each of these stages, the cell is physically arranging itself to replicate and divide nuclear material. ***Cytokinesis***, a process that follows mitosis, is the division of the actual cell into the two new daughter cells. During cytokinesis a cell plate forms between the dividing cells and grows outward to the cellular wall, separating the two new cells. Each new daughter cell has a nucleus with a full set of chromosomes and half of the cytoplasm, containing plant organelles.

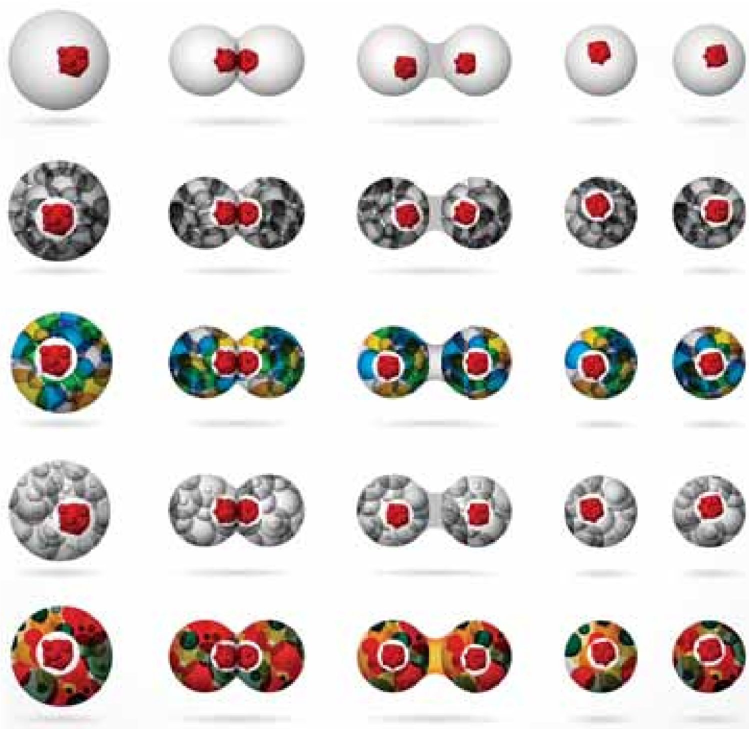

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Figure 9-16. Observe how the cell changes through each of the stages of mitosis until two new daughter cells with identical genetic information are formed.

Sexual Reproduction

Sexual reproduction in both plants and animals is the union of a female and male gamete that results in a new organism that is genetically different than either of its parents. Plant breeding uses the process of sexual reproduction to develop new, novel, and enhanced plant material. Sexual reproduction in plants occurs through meiosis and fertilization. ***Meiosis***, like mitosis, involves a nuclear division, but rather than replicate the number of chromosomes, the cell's chromosomes are divided in half. Through ***fertilization***, the male gamete combines with the female gamete to create a genetically unique organism.

Chromosomes

Chromosomes are cellular structures that carry the genetic information of a plant. Every species has a specific number of chromosomes, found in the nucleus. For example, humans have 46 chromosomes, dogs have 78 chromosomes, and common wheat has 42 chromosomes, **Figure 9-17**. Chromosomes are found within all the somatic (vegetative) cells of the plant and are considered to be ***diploid*** (have a full set of chromosomes, one from each parent plant). A plant's entire set of chromosomes is called the ***genome***.

Chromosomes are made up of filament-like threads called chromatin. ***Chromatin*** contains DNA and proteins. ***Genes*** are specific sequences of nucleotide pairs on a DNA molecule that hold the information to build and maintain cellular processes and pass genetic traits to offspring. Different genes are responsible for any number of physical traits and drive biochemical processes and responses in plants.

In the reproductive cells of the flowers, gametes contain a ***haploid*** set of chromosomes (a complete set of chromosomes from one parent). During fertilization, male and female haploid nuclei fuse to form a diploid cell called the ***zygote***.

Plants		
Organism	**Species**	**Diploid (2N) Chromosome Number**
Alfalfa	*Medicago sativa*	32
Avocado	*Persea americana*	24
Barley	*Hordeum vulgare*	14
Bermuda grass	*Cynodon dactylon*	36
Cashew	*Anacardium occidentale*	42
Corn (maize)	*Zea mays*	20
Cotton, upland	*Gossypium hirsutum*	52
Garden pea	*Pisum sativum*	14
Grape	*Vitis vinifera*	38
Mango	*Mangifera indica*	40
Oats, white	*Avena sativa*	42
Onion	*Allium cepa*	16
Papaya	*Carica papaya*	18
Peanut	*Arachis hypogaea*	40
Pineapple	*Ananas comosus*	50
Potato	*Solanum tuberosum*	48
Rice	*Oryza sativa*	24
Soybean	*Glycine max*	40
Squash	*Cucurbita pepo*	40
Sugarcane	*Saccharum officinarum*	80
Tomato	*Lycopersicon esculentum*	24
Wheat, common	*Triticum vulgare*	42
Animals		
Organism	**Species**	**Diploid (2N) Chromosome Number**
Human	*Homo sapiens*	46
Cat	*Felix domesticus*	38
Cattle	*Bos taurus*	60
Chicken	*Gallus domesticus*	78
Dog	*Canis familiaris*	78
Fruit fly	*Drosophila melanogaster*	8
Grasshopper	*Melanoplus differentialis*	24
Honeybee	*Apis mellifera*	32
Horse	*Equus calibus*	64
House fly	*Musca domestica*	12
Mosquito	*Culex pipiens*	6

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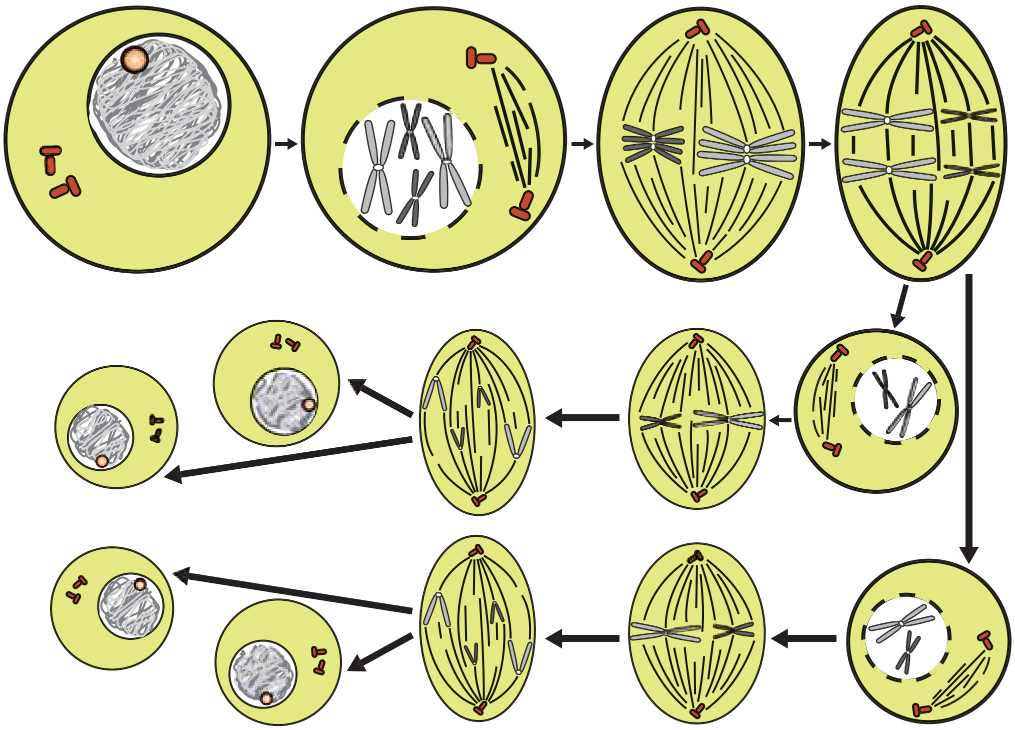
Figure 9-17. Note the vast differences in chromosome numbers among different species.

Meiosis

Prior to the process of meiosis, each chromosome replicates itself. As the cell begins the first step of meiosis I, **Figure 9-18**, pairs of chromosomes line up in the center of the cell where a phenomenon called crossing-over occurs. Meiosis is responsible for genetic diversity. During crossing-over, genes are exchanged between matching chromosomes, so that each chromosome becomes a mosaic of genes from the male and female parent plants. This makes new and unique arrangements that can impact the way a plant grows or looks. This is a critical factor for genetic recombination in organisms. The cell continues to divide in half, but each cell still has a diploid number of chromosomes, with each cell containing a mix of genes from the parent plants. Meiosis II now happens, similar to mitosis, and divides the cells again. The end result of meiosis I and II in one diploid cell is four haploid daughter cells (cells that contains a single set of chromosomes) that will develop into male gametes (sperm) or female gametes (eggs).

Fertilization

Fertilization is the fusion of the male and female gamete haploid nuclei to form the diploid zygote. In plants, the male gamete (sperm) is found protected within pollen grains. Both gymnosperms and angiosperms produce pollen-bearing male gametophytes (the multicellular haploid stage). In gymnosperms, the pollen travels to the female cones, which



Dreamy Girl/Shutterstock.com

Figure 9-18. The stages of meiosis during sexual reproduction. The chromosome number is halved to create haploid sex cells (sperm and egg cells).

have ovule-bearing scales, **Figure 9-19**. In angiosperms, the pollen travels from the anthers to the stigma. This process is pollination. After pollen lands on the stigma, a pollen tube grows through the style until the sperm can reach the eggs (ovules) contained within the ovary and fertilization occurs.

srekap/Shutterstock.com

Figure 9-19. Gymnosperms, unlike angiosperms, do not have flowers. Instead they have male and female cones. This is the female cone of a Douglas fir.

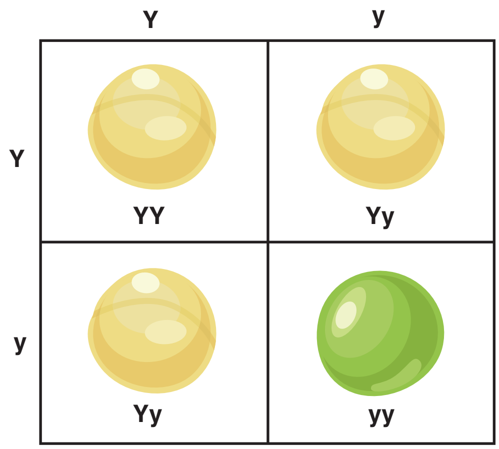
Plant Breeding Principles

Gregor Mendel's famous cross-pollination of the common garden pea (*Pisum sativum*), **Figure 9-20**, led to the discovery of a few basic principles of gene inheritance. It also played an essential role in establishing early plant breeding methods. Mendel worked with peas that had been inbred, or self-fertilized, for generations and, therefore, were fairly uniform or ***homozygous*** (having identical pairs of genes for a pair of hereditary characteristics). He took peas with ***alleles*** (one of a number of variant forms of the same gene) for yellow seeds and cross-pollinated them with peas that had showed the trait for green seeds. The resulting offspring were entirely yellow-seeded peas and were considered hybrids and the first filial, or F1, generation. Because there were no green-seeded peas that resulted from this cross, the yellow-seeded trait is considered ***dominant*** (the relationship between one allele that is expressed over a second allele). The green-seeded trait is considered ***recessive*** (the relationship where one allele is only expressed when the second, dominant allele is not present.). When an F1 generation is self-fertilized, the progeny are called the F2 generation. The F2 generation of Mendel's crossing experiment produced a 3:1 ratio of yellow-seeded peas to green-seeded peas. A Punnett square, **Figure 9-21**, further illustrates the outcomes of the cross, showing one dominant homozygous yellow seeded progeny (YY), two heterozygous (Yy) offspring, and one recessive (yy) homozygous offspring. Mendel determined that seed color is a trait that is controlled by the genes of both parents.

There are also times when neither gene is dominant, and the results are an intermediate phenotype. For example, in some petunias cross-pollinating a homozygous red petunia with a homozygous white petunia will result in offspring having some pink flowers.

Geo-grafika/iStock/Thinkstock

Figure 9-20. The common garden pea played a key role in understanding basic principles of gene inheritance.



Ksena Shurubura/Shutterstock.com

Figure 9-21. This Punnett square shows the relationship between the cross of a yellow-seeded pea and a green-seeded pea. Note the 3:1 ratio in the F2 generation.

AN NGUYEN/Shutterstock.com

Figure 9-22. Incomplete dominance will show traits of both parents. For example, pink petunias may result from cross pollinating red and white petunias.

DutchScenery/Shutterstock.com

Figure 9-23. These hybrid peppers have been developed by plant breeders to resist diseases.

This is called ***incomplete dominance***. It is a phenomenon in which a plant shows characteristics of both parents, **Figure 9-22**.

The genetic composition of an organism, often in reference to a particular trait, is called the ***genotype***. The genotype influences how a plant grows and develops. Environmental conditions such as temperature, water availability, and nutrient availability also influence the way a plant grows and develops. The interaction between a plant's genetic makeup and the environment is called its ***phenotype***. The phenotype is a visible expression of an organism's observable characteristics. For example, the yellow and green colorings of Mendel's peas are phenotypic characteristics.

Plant breeders and plant geneticists use this information to determine how to select parents for breeding purposes. Selected parents will have desirable characteristics that, when crossed with other selected parent plants, will result in offspring that have those desirable traits. For example, a pepper breeder may want to decrease the capsaicin (amount of heat) levels in a plant and also have effective disease resistance. To do this, the plant breeder will use parents with these traits and cross-pollinate, **Figure 9-23**.

The Plant Breeding Process

Plant breeders select a parent to be the female, or seed-producing parent, and a parent to be the male. All the male floral parts are removed from the maternal (female) parent. This process is called emasculation and it eliminates the possibility of the flower to self-pollinate. The stamens should be removed before the anthers release the pollen. To cross-pollinate a plant, a breeder removes the stamen from the paternal (male) parent using tweezers and brushes the anther across the stigma of the maternal parent. The seeds are then saved and planted. The offspring are evaluated for the presence of desired characteristics.

"The secret of improved plant breeding, apart from scientific knowledge, is love."
—Luther Burbank

Plant Mutations

Mutations are naturally occurring genetic changes that affect the appearance and functions of a plant. Mutations are heritable and can be called a chimera or sport. Mutations can also be induced through radiation or chemicals.

Most mutations are not desirable and have adverse effects on a plant. Examples include a lack of chlorophyll and the inability to photosynthesize. A few mutations can produce desirable traits, such as a unique ornamental or growth habit. ***Chimeras*** are a type of mutation that allows two genetically distinct tissues to coexist, **Figure 9-24**. ***Sports*** are tissue mutations that occur in vegetative cells. For example, a branch or stem will show a specific observable trait difference, such as variegated leaves or flower color. Witches' broom is a growth phenomenon that shortens the internode spacing, causing dwarf plants. Although insects, viruses, or diseases can cause witches' broom, it can also be caused by a genetic mutation.

Kristina Gruzdeva/iStock/Thinkstock

Figure 9-24. The variegated snake plant is an example of a chimera. Two genetically different tissues exist within the same plant. Can you think of any other examples of chimeras that you may have seen?

Careers

The study of plant growth and development can lead to careers in the basic and applied sciences. Understanding the plant processes allows researchers to develop best practices for managing and growing plants.

Plant Physiologist

Plant physiologists have a broad systems understanding of whole plant processes, all the way down to the cellular level. They use this knowledge to examine the physical, chemical, and biological functions of living plants. Plant physiologists explore how plants grow and study the components required to drive the development process, from germination to death. Many plant physiologists are researchers in colleges and universities. They perform basic research that can inform applied practices used in horticulture. For example, a plant physiologist might look at the pathways by which a plant can take in toxic pollutants. A horticulturist can use this information to plant species that are most effective in decontaminating polluted soil.

STEM Connection

Induced Mutations in Plant Breeding

The use of radiation, such as X-rays, gamma rays, neutrons, and chemical mutagens to induce variation, has been used to improve both floriculture and agricultural crops. In crops where diversity for a given trait is low or nonexistent, induced mutation provides a way to incorporate novel traits into the traditional plant breeding and selection process. Through mutagenesis (induced mutation), pears have improved disease resistance and spineless pineapples and seedless grapefruit have been developed.

Career Connection

Joseph Tychonievich

Plant Breeder

Photograph by Joseph Tychonievich

Joseph Tychonievich is an independent plant breeder and author who was “mesmerized by the magic of plants” as a young child. For the past ten years, he has been breeding nursery plants. Joseph cultivates tree and shrub plants as well as herbaceous perennials and vegetables. He has developed unique alpine plants that are popular with specialty gardeners and also finds old-fashioned annuals, such as heirloom zinnias and hyacinths of the 1820s, really interesting. His work has made him a prominent figure in the horticulture world.

Joseph encourages young gardeners to “Just try stuff. Nursery breeders can find a niche and be very successful. Whether it is growing plants, working in a nursery, blogging, taking photographs, or breeding plants, you have to pursue an idea.” As an independent breeder, Joseph has a great deal of flexibility that includes self-employment, independence, travelling, writing, lecturing, and networking with other horticulturists. His blog provides a unique platform to connect with interested gardeners of all ages around the world.

A bachelor’s degree is required for entry-level laboratory positions, both in universities and private industry. Graduate degrees will open doors for high-level research positions at these same institutions, as well as in government agencies such as the United States Department of Agriculture (USDA) or the Environmental Protection Agency (EPA).

Plant Breeder

Plant breeders strive to improve the overall characteristics of various plants for increased production and profitability. Plant breeders work with agronomic, horticultural, and forestry crops. They use traditional breeding methods of cross-pollination as well as newer processes that apply biotechnology and molecular techniques to enhance the breeding process.

Plant breeders generally need a graduate degree (master’s or higher) in a related plant science field (horticulture, agronomy, forestry, botany, plant pathology, biology, entomology, soils). Possible careers include working at a public university to create new cultivars that support growers in that state or region. Many private companies hire plant breeders to create desirable hybrids wanted by commercial growers and home gardeners. These types of plants are profitable for the company.

CHAPTER 9

Review and Assessment

Chapter Summary

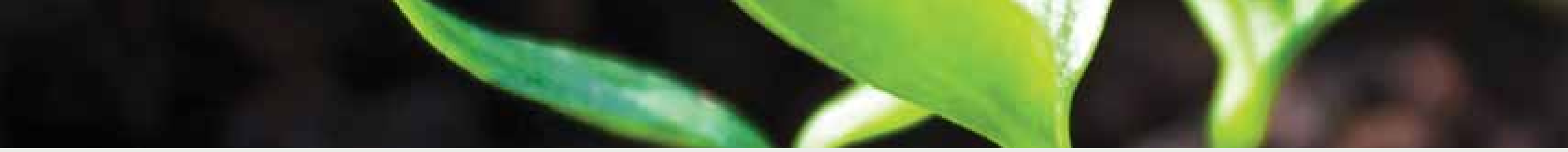
- The process of photosynthesis enables plants to capture energy from the sun and convert carbon dioxide and water into sugar that can be used by plants and animals as sources of energy. Oxygen is released as a by-product.
- The process of photosynthesis can be divided into two parts: light-dependent reactions and light-independent reactions.
- The sugars produced through photosynthesis are used as energy created by respiration to drive basic plant functions. Respiration converts glucose in the presence of oxygen to a form (ATP) that can be used by plants.
- Transpiration is the process of water being drawn up from the roots through the xylem and released through the stomata. Evaporation powers the process of transpiration through water's cohesive properties.
- The transpiration stream powers the movement of inorganic nutrients throughout the plant. Translocation is the process of moving photosynthetic products (sugars) from sources to sinks.
- Plant reproduction occurs by both mitosis (asexual reproduction) and meiosis (sexual reproduction). Somatic cells divide using mitosis and sexual cells divide through meiosis and allow for genetic variation to occur.
- Plant breeding improves the characteristics of plants by increasing yield, vigor, nutritional content, ornamental value, stress tolerance, and growth habit.
- Plant mutations are naturally occurring genetic changes that affect the appearance and functions in a plant. Mutations can happen at random or can be induced by radiation or chemicals.
- The study of plant growth and development can lead to careers such as plant physiologist and plant breeder.

Words to Know

Match the key terms from the chapter to the correct definition.

A. allele
B. carotenoid
C. Casparian strip
D. chimera
E. chlorophyll
F. chromatin
G. chromosome
H. cohesion
I. cytokinesis
J. diploid
K. dominant
L. fertilization
M. genotype
N. grana
O. haploid
P. homozygous
Q. incomplete dominance
R. phenotype
S. recessive
T. relative humidity (RH)
U. sport
V. stroma
W. thylakoid
X. turgor

1. A filament-like structure that contains DNA and proteins that makes up chromosomes.
2. A cell that contains two complete sets of chromosomes.
3. Cellular structures that carry the genetic information of a plant.
4. A phenomenon where a plant displays characteristics of both parents.
5. The genetic makeup of an organism, often in reference to a particular trait.
6. The aqueous space outside of the grana within the chloroplast.
7. Water pressure within plant cells that create cellular rigidity.
8. The amount of water vapor in the air compared to the amount of water vapor that air can hold at a given temperature.
9. A stack of thylakoid disks found within the chloroplast.
10. Having identical pairs of genes for a pair of hereditary characteristics.
11. The relationship between one allele that is expressed over a second allele.
12. One of a number of variant forms of the same gene.
13. A type of mutation that allows two genetically distinct tissues to coexist.
14. A plant pigment that reflects yellow, orange, and red light and assists in capturing light energy.
15. The process in which the cytoplasm of a single cell is divided to form two daughter cells and the cell plate is formed.
16. The process by which the male gamete combines with the female gamete to create a genetically unique organism.
17. A type of tissue mutation that occurs in somatic (vegetative) cells.
18. A visible expression of an organism's observable characteristics.
19. Folded membrane inside the chloroplasts that serves a key function in the photosynthetic process.
20. The relationship where one allele is only expressed when the second, dominant allele is not present.
21. A cell that contains a single set of chromosomes.



22. A green pigment located in the chloroplasts of plant cells that is a receptor of light energy in the red and blue wavelengths.
23. A waxy barrier that rings the endodermal cells in the roots.
24. A property of water in which hydrogen bonding between adjacent water molecules allows the water to be pulled upward through the plant.

Know and Understand

Answer the following questions using the information provided in this chapter.

1. What is photosynthesis and why is it important to life on earth? What element is created as a by-product of photosynthesis?
2. Where do light-dependent and light-independent reactions occur?
3. Name the three types of light-dependent reactions and plants that use these pathways.
4. Where does respiration occur within the cell?
5. Describe the process of respiration.
6. Why are water-saturated conditions a problem for some plants?
7. How does raising and lowering temperatures affect plant growth?
8. List the benefits of transpiration in plants.
9. What happens if a plant experiences excessive water loss?
10. What is the role of water in plant growth?
11. What factors affect rates of transpiration?
12. Describe the influence of relative humidity on transpiration.
13. How do water and nutrients enter plant roots?
14. Describe the way sugar is translocated throughout the plant.
15. List the characteristics that plant breeders breed for in plants.
16. Summarize the steps of mitosis.
17. Compare and contrast mitosis and meiosis (asexual and sexual reproduction).
18. Identify the role that chromosomes play in a plant.
19. Detail the reasons why meiosis is responsible for genetic diversity.
20. Explain the process of pollination.
21. Explain the process of cross-pollination.
22. What does a plant breeder career involve? What education is needed for this career?

Thinking Critically

1. Bald cypress trees are typically found growing in soggy soil. Water-saturated soils limit oxygen levels needed for respiration. How do you think these trees get enough oxygen to drive the energy-making process of aerobic respiration?
2. Many succulents have a CAM metabolism, opening their stomata at night to minimize water loss. In what kind of environment do you think these plants typically grow? How might they do in another kind of environment?

3. Plant breeders are constantly evaluating and selecting plants for desired characteristics. Describe the ideal plant for your garden and detail the breeding steps you would take to create your plant. What do you need? How long would it take? Is this possible?
4. American chestnut trees have all but disappeared from the Appalachian Mountains due to a fungus from Asia that caused a destructive blight. Can you think of way that scientists might be able to save the chestnut?

STEM and Academic Activities

1. **Science.** Light powers the process of photosynthesis. Plants have multiple pigments that can capture different wavelengths of light. Create an experiment using different types of light and record your observation on the impact light quality has on plant growth.
2. **Science.** Transpiration in plants can be approximately measured by weighing a potted plant before and after a certain period of time. Take a small potted plant and water thoroughly. After the water has drained, weigh the entire potted plant and record the weight. Cover the soil surface with plastic wrap to prevent evaporation from any surface except for the leaves. Observe the plant over time and record the weight each day. How much water is lost after a day? A week? What do you think will happen if you try this in different environmental conditions or with other plants? Experiment and compare and contrast the results.
3. **Science.** Try your skills at plant breeding by cross-pollinating two plants and evaluating the resulting progeny. First find two petunias with different flower colors. Petunias are easy to grow and easy to cross-pollinate. Decide which plant will be the seed parent and which will be the male parent. Emasculate the flowers on the seed parent. Using tweezers, pluck a stamen from the other plant and brush pollen on the sticky stigma of the petunia. Be sure to label your cross with a tag on the pollinated flower. Continue to grow the seed parent until fruit and seeds mature. Plant the seeds and evaluate your new plants for characteristics they might exhibit. How are they the same as the parents? How are they different?
4. **Social Science.** Plant breeding can seem like a science-fiction story, with breeders being able to “design” plants by choosing the specific physical and personality traits desired. Do you think this is a good idea? Why or why not? Use specific reasons and examples to support your position.
5. **Language Arts.** Write a blog post about one of the plant experiments you are conducting from the activities above. Describe the details of your experiment, including the methods, the data, and any conclusions you can draw. Include clear descriptions and explanations that would allow your reader to replicate your work if desired.
6. **Language Arts.** Work with your teacher to set up a mock interview for a job position in plant physiology, plant breeding, or a related field. Prepare yourself to effectively convey the qualities you possess to be a successful applicant. Try to incorporate good communication skills including speaking clearly and enthusiastically about your experiences and skills.

Communicating about Agriculture

1. **Reading and Speaking.** Using your textbook, library resources, and the Internet, research plant breeding of edible horticultural crops. Focus on the history and the way in which plant breeding has changed food security around the world. Create a poster to illustrate your findings and design(s) and present it to your peers.
2. **Listening.** As classmates deliver their presentations on plant breeding, listen carefully to their ideas. Write down any questions that occur to you. Later, ask questions to obtain additional information or clarification from your classmates as necessary.
3. **Reading and Speaking.** Working in groups of three students, create flash cards for the Words to Know in this chapter. On the front of the card, write the term. On the back of the card, write the pronunciation and a brief definition. Use your textbook and a dictionary for guidance. Then take turns quizzing one another on the pronunciations and definitions of various words.

SAE Opportunities


USDA

1. **Exploratory.** Plant physiology is a broad subject that encompasses a number of more narrow disciplines. Molecular biology is a growing field that looks at the molecular functioning of plants. Job shadow a researcher in this industry. What is the purpose of this job position? What are the daily responsibilities? What career path do you need to create to become a molecular biologist?
2. **Exploratory.** Research how to manage relative humidity in a greenhouse. Can it be managed? How does this affect the plants growing in the greenhouse? What are the costs involved? Why might this be important to know as a grower?
3. **Improvement.** Find a location on your school campus that has been neglected. Consider creating a small pocket garden and growing plants that require minimal watering. What kind of photosynthetic pathway do you think these plants have? Why?
4. **Entrepreneurship.** Create a new cultivar to sell at your school plant sale. Find an easy plant to cross-pollinate (make sure they are not patented) and sell the seeds as a niche marketing product.