Flowering Plants

STRUCTURE AND INDUSTRIAL PRODUCTS

AISHA SALEEM KHAN

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Dedicated to my dear and loving father without his support I would not have been able to write this book

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Preface

My inspiration for writing a book on Applied Plant Biology came from many authors whose work has captivated my imagination, since I was an undergraduate student. I have been teaching Applied Plant Biology to undergraduate and postgraduate students for the last 12 years. It is not only my area of specialization but my passion as well.

Being a botanist, I always felt the urge for a book which relates plant structure with their important functional products and commercial applications. I believe that angiosperms structure and their important products need to be discussed together in order to have a clear understanding of how the plant architect influences the formation of important products.

The following book relates morphological aspects of flowering plants alongwith their products in different industries in a unique, informative, more conceptual and an interesting way with research-based and updated knowledge. There is a strong need to correlate flowers of angiosperms with their compounds of industrial importance as it is rare to find books which characterize and highlight important products of angiosperms from flowers, fruits and seeds alongwith their morphology. I am sure that with the necessary topics covered, the following book can be introduced as a textbook for all students of plant biology as it will capture their interest towards plants biology. Students all over the world find the study of plants more or less difficult or dry, which does not always aspire their general interest. One of the reason behind this is that the general consensus amongst the academic scientific community has negated the plant sciences its real position due to other emerging trends in biological sciences. Consequently, subjects characterized in the realm of fundamental sciences are loosing their inert value as one of the integral components in comprehending biology.

Although this book is primarily designed for the students of plant sciences, it is also be helpful for researchers who are associated with the different industries, as it covers plants products of commercial value that are being used by food, agriculture, pharmaceutical, beverages, textile, dye, floriculture, perfume, and cosmetic industries.

This book covers topics like making of bioengineered bacterial perfumes from roses, development of transgenic herbivores resistant plants, modern trends in developing ornamental medicinal plants, plant-derived nutraceuticals, plant pigments as dye-sensitized cells and also the role of plant hormones as antiaging molecules. Various distillation methods and techniques like supercritical CO_2 methods for extraction of essential oils, gas chromatographic and mass spectrometric techniques are also included. Life cycles of plants and evolutionary relationships in molecular phylogenetics are included with future perspectives to develop student's interests in plant biology.

It also explains diversity in floral cells which relate their metabolic activities, how cells of sepals differ from petals, ovary and stamens, and how they manage carbohydrates to fulfill their energy demands? In addition, it also covers the formation of important products within floral cells, intercellular and intracellular communications and different steps which are involved in making them commercial; molecular aspects of pollination, pigmentation and reproduction events in angiosperms are also discussed.

Acknowledgements

I am thankful to my dear students who motivated me and suggested me to write a book on the following subject. I am extremely thankful to Sara Dar, designer, for drawing computer illustrations of this book. I am also thankful to Dr. Samina Mehnaz, my chairperson for motivating me throughout writing of this book and also to my colleagues Dr. Aafia Aslam and Dr. Asma Maqbool. My sincere thanks are to my family members, my siblings and my dear friends.

I am also thankful to John Wiley & Sons for giving me this opportunity and for making my dream come true.

1

An Introduction to Flowering Plants: Monocots and Eudicots

There is no doubt about it that plants are main producers of ecosystem and important in every aspect of our daily lives. Many products which are used in food, nutraceutical, pharmaceutical, textile, cosmetics, perfumery, coffee, tea and beverage industries are in fact derived from plants. They are biosynthesized in different parts of plants and are known as *natural products* or *secondary metabolites*. Many of these compounds are defensive in nature which are produced during primary metabolic activities in plants. Many pigments in flowering plants are also secondary metabolites which are crucial for their pollination. Secondary metabolites include alkaloids, flavonoids, betalains, glycosides, tannins, terpenoids and saponins. They will be introduced in the next chapter.

This book deals with flowering plants, that is, *angiosperms* as they make one of the abundant group of plants of economic importance. However, before discussing major products of angiosperms, their biosynthesis and applications, it is important to discuss what are angiosperms? How did they evolve? What is their body organization and what kind of cells they have? So in the next section, a brief introduction of angiosperms and their classification is discussed.

1.1 An Introduction to Major Group of Angiosperms: Monocots, Eudicots and Basal Angiosperms

All plants are considered to be a group of related organisms which are capable to synthesize their own sugars during photosynthesis, possess the cell wall, and generally with the differentiation of their bodies in roots, stems, leaves, flowers or flower- like structures. But recent trends in molecular phylogenetics have shown that they are not as much closely related as thought before. In fact, plants can be best described as 'a group of different organisms which evolved independently during course of evolution and share similar characteristics like ability to synthesize their own food within their chloroplasts, have chlorophyll *a* as a necessary photosynthetic pigment and possess the cell wall which largely comprises of cellulose'. Their body is differentiated in vegetative and reproductive organs (spore or seed-producing structures) and are therefore classified in one kingdom *plantae*. Division within kingdom plantae is based either on the presence or absence of vascular tissues (xylem and phloem) or spore-producing structures. *Bryophytes* like liverworts, hornworts and mosses are non-vascular spore producing plants while *pteridophytes* are vascular plants which produce spore, for

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example, ferns, horsetails and clubmossses. Other two major groups are seed-producing plants, that is, *gymnosperms* which produce seeds which are not enclosed within their ovaries, and *angiosperms* or flowering plants, in which seeds develop within carpels and are covered by ovary wall.

Angiosperms also known as *flowering plants* are the largest monophyletic group of seed producing plants which have evolved many efficient ways of survival over the period of time. They are unique from other group of plants due to the development of *endosperm* (nutritive tissue around embryo within seeds), flowers with carpels and stamens having two pairs of pollen sacs and phloem for transportation of sugars. Their fossils are over 135 million years old. Angiosperms are considered to be close relatives of living gymnosperms but some recent evidence suggested that seed ferns represent sister group to angiosperms. They are relatively evolved group of plants as compared with gymnosperms as they possess several mechanisms which ensure successful asexual and sexual reproduction, one of the main reason which makes them one of the abundant group of seed plants.

Although *monocots* (angiosperms with one cotyledons) and *dicots* (angiosperms with two cotyledons) are referred as two main groups of angiosperms but modern classification which is based on molecular evidences have characterized angiosperms as *core and basal* angiosperms according to their *monophyletic* origin (descendants of common ancestors) and facts provided by molecular data including studies from DNA sequences from chloroplasts gene *rbcL*. Therefore, modern system of plant taxonomy, that is, *Angiosperms Phylogeny Group* (APG) system is a molecular-based systematics which retains order and families of Linnean systems and includes groups which are monophyletic. APG I was published in 1998 which was followed by APG II in 2003 (Chase *et al.*, 2003) and APG III in 2009 (Bremer *et al.*, 2009) and then APG IV in 2016. However, further development in molecular techniques, advancement in techniques related to metabolomics and proteomics is exploring the molecular phylogenetics which will form foundation of evidence-based classification of flowering plants.

Evolutionary evidences suggest that *basal angiosperms* which are characterized by absence of xylem vessels are primitive, however, some recent phylogenetic analysis reported that *Amborella trichopoda* is sister to all extant angiosperms and is at the base of angiosperms phylogenetic tree. They are composed of only few species which include many aquatic plants like water lilies (Figure 1.1), *Amborella* and star anise. *Core* angiosperms are represented by monocots and *core eudicots*. They include three major groups including *monocots*, *eudicots* and *magnoliids*, and the latter group was once considered to be dicots but now it is placed in a separate group. Important magnoliids include plants like avocado, black pepper, magnolia, nut-meg, bay leaf, tuliptree or yellow poplar.

Eudicots also known as *true dicots*, composed of more than 75% of angiosperms and are characterized by their monophyletic origin and presence of *tricolpate* pollens (having three apertures). This group of angiosperms represents abundant clade of angiosperms. Figure 1.2 shows a cladogram of flowering plants based on information from APG I, II and III. A *cladogram* represents an evolutionary diagram which is used to explain evolutionary relationships within a group of related organisms which share common ancestors. Orders of basal angiosperms (Amborellales, Nymphaeales and Austrobaileyales) represent primitive groups whereas core eudicots are represented as advanced or modern group of flowering plants. Magnoliids like Laureales, Magnoliales, Canellales and Piperales are evolved with monocots. Eudicots represent abundant group of flowering plants, among which core eudicots include two highly evolved and

Figure 1.1 (a-b) Basal angiosperms, (a) *Nymphaea alba* from family Nymphaeaceae, (b) *Magnolia* sp. is another basal angiosperm which belongs to family Magnoliaceae.

diverse clades which evolved separately are *asterids* (lamiids and campanulids) and *rosids* (fabids and malvids) (based on APG III) which are classified on the basis of their tendency to produce fused or free petals (Figures 1.3 and 1.4). Evolutionary traits, apomorphies, which are important in classification are represented where the origin of a clade takes place. Eudicots represent group of many economically important plants like members of family Apiaceae, Asteraceae, Brassicaceae, Cucurbitaceae, Fabaceae, Malvaceae, Rosaceae and Solanaceae.

Other main group of flowering plants, that is, *monocots* represent one of the highly evolved clade with monophyletic origin (Figure 1.5). They are characterized by presence of only one cotyledon, non-woody stem, fibrous roots, long and slender leaves with parallel venation and scattered vascular bundles. They produce inconspicuous, mostly non-fragrant flowers with floral parts in multiple of three often which are arranged to form a *spikelet* in case of grasses. Table 1.1 shows comparison of monocots and eudicots. *Commelinid* clade represents most derived group of angiosperms which includes many plants from Arecales, Commelinales, Poales and Zingiberales. Monocots include palms, orchids and grasses which evolved about 60 millions years ago and are composed of almost 10,000 species. Fossils of palms and members from arum family are the oldest known monocots which are reported to found in rocks almost 100 millions years old. Monocots include many economically important plants which make our staple food like all cereals and grasses are monocots. They are important source of biofuel and bioenergy.

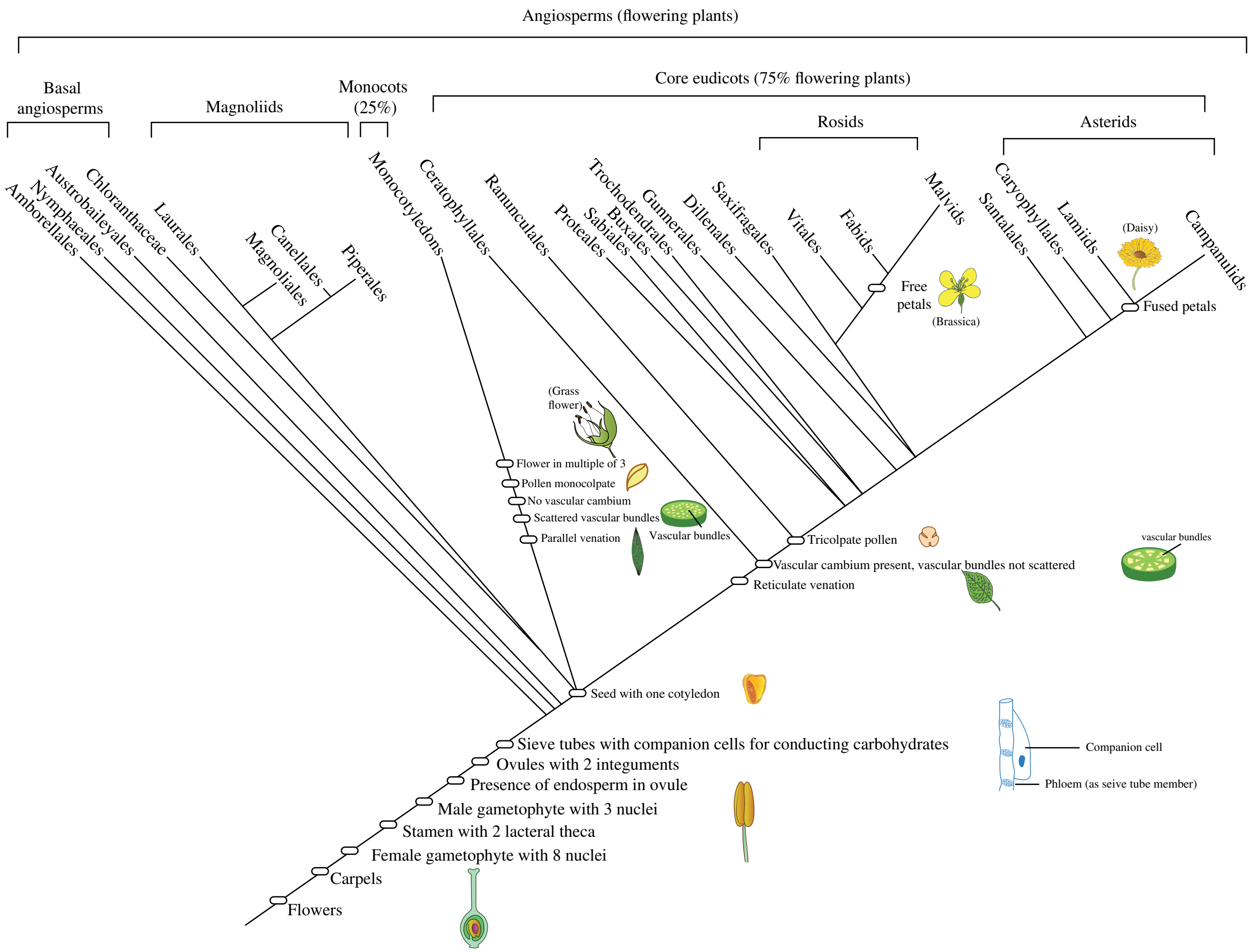

Figure 1.2 A cladogram of angiosperms based on information from the Angiosperms Phylogeny Group (APG III, 2009) (Bremer *et al*., 2009).

(a) (b)

(c) (d)

(e)

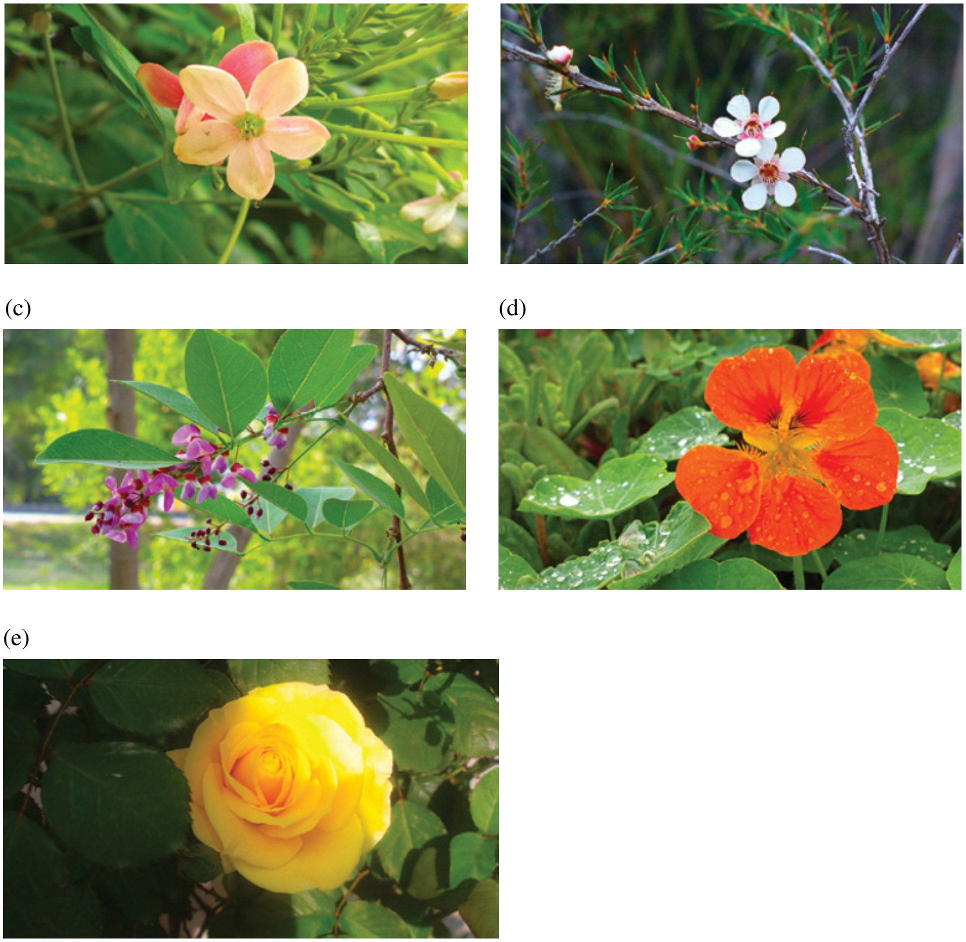

Figure 1.3 (a-e) Rosids (fabids and malvids) are characterized by the presence of free petals (a) *Quisqualis indica,* (b) *Chamelaucium uncinatum,* (c) *Millettia peguensis* is an economically important plant with insecticidal properties and antiviral activities, (d) *Tropaleum majus* is an ornamental member of family Tropaeolaceae, and (e) *Rosa* sp. which belongs to Rosaceae is one of the popular ornamental and medicinal shrub.

Before describing the functional products of angiosperms, their biosynthesis and industrial uses, it is important to revise and update knowledge about angiosperms cell. So the following section will be dealing with the structure of an angiosperm cell along with some updates.

1.2 Plant Cell: Revisions and Few Updates

All plant cells are surrounded by the *cell wall* which not only protects them but also gives them definite shape. A lipoprotein bilayer, that is, *plasma membrane* is present next to the cell wall and regulates the movement of molecules in and out of plant cells.

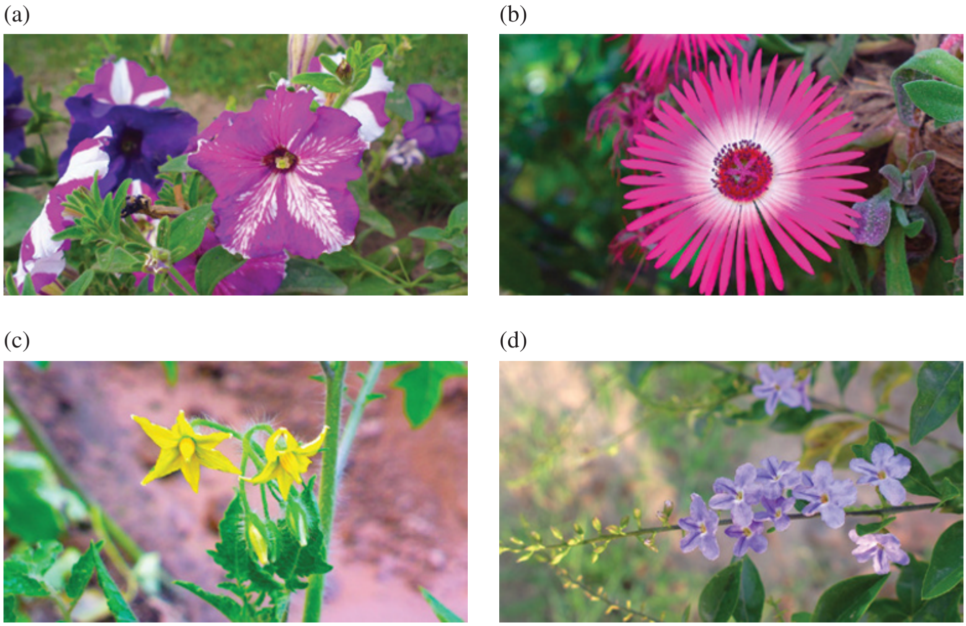

Figure 1.4 (a-d) Asterids (lamiids and campanulids) are core eudicots which are differentiated from other eudicots due to the presence of fused petals (a) *Petunia hybrid,* (b) Daisy, (c) *Lycopersicon esculentum,* (d) *Duranta erecta*.

(a)

Figure 1.5 (a-e) Monocots are composed of many economically important plants: (a) Wheat (*Triticum aestivum*) is a major cereal, bioenergy crop and a staple food worldwide.

Figure 1.5 (Cont'd) (b) Arum lily (*Zentedeschia aethiopica*) showing spadix (in yellow) and spathe, (c) *Epipremnum aureum* is a popular house plant which removes many indoor pollutants, such as formaldehyde, xylene and benzene, (d) *Bambusa* sp., (e) *Canna indica* also known as canna lily is used in constructed wetland for the removal of organic pollutants and heavy metals.

Plasma membrane encloses many membrane-bound structures, that is, *organelles* which are present within a fluid *cytosol* which is the site for main metabolic activities of cell. Main organelles which are part of almost every plant cell include nucleus, mitochondria, plastids, vacuoles, endoplasmic reticulum, Golgi apparatus and ribosomes. However, in addition to this, plant cell may also contain microbodies, tannosomes, anthocyanoplasts and oil bodies depending upon their physiological role (Figure 1.6).

1.2.1 A Cellulosic Cell Wall is Crucial for all Plant Cells

Angiosperms show diversity in chemical composition of their cell wall which is the outermost covering of every plant cell whether it is a cell of root, leaf, stem, flower, fruit or seed. Each cell of these organs possess their own cell wall which gives them rigidity, support and a definite shape along with *cytoskeleton* which is composed of a network of microtubules and actin filaments. Cytoskeleton is involved in orientation of cellulose

Table 1.1 A comparison of two major group of core angiosperms.

Characteristics	Monocots	Eudicots
Root	Fibrous, vascular bundles are collateral	Taproot, xylem in centre
Stem	Soft, herbaceous with scattered vascular bundles	Soft in non-woody herbs or woody but vascular bundles are compactly arranged
	Wheat (*Triticum aestivum*) 	**Coriander (*Coriandrum sativum*)** 
Leaf	Parallel venation 	Reticulate venation 
Flower	Ear of wheat 	Umbel inflorescence of coriander 
Fruit	Wheat hull or husk 	Coriander fruit 
Seed	Wheat grains (monocots) 	Seeds showing two cotyledons (eudicots) 
Pollination	Mostly wind pollinated	Pollination through insects and animals
Pollen grains	Monocolpate	Tricolpate

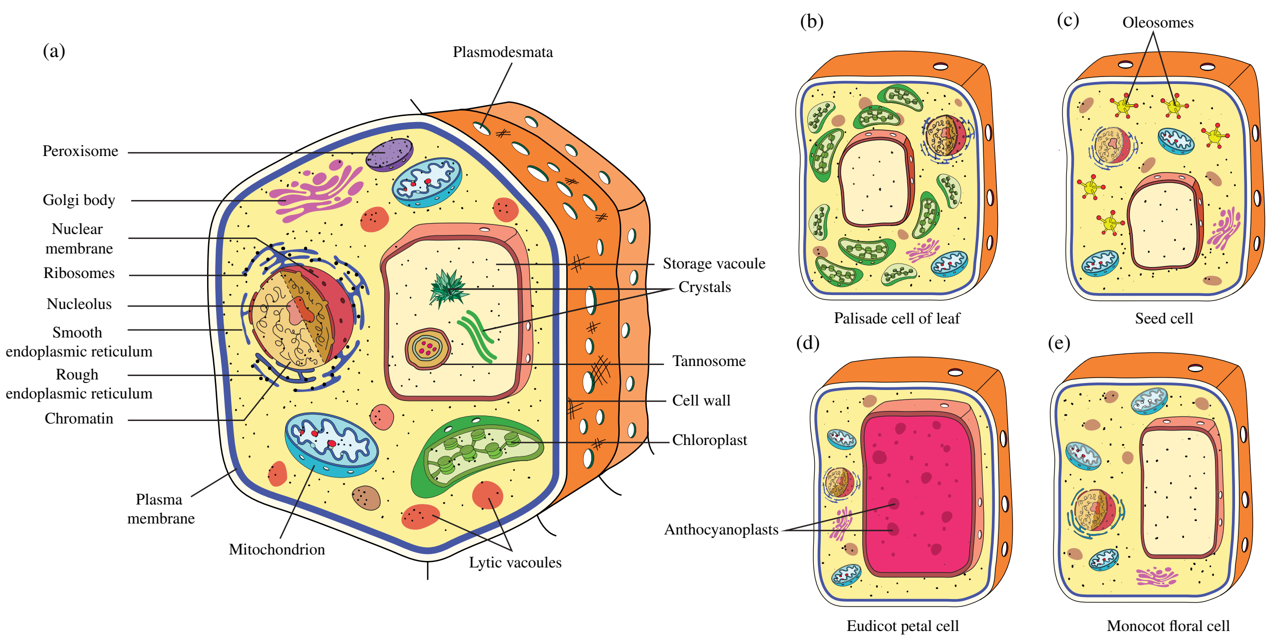

Figure 1.6 (a-e) Plant cells show differences depending upon their role: (a) A typical plant cell, (b) Cells of mesophyll of leaves contain abundant chloroplasts due to their role in photosynthesis, (c) Seed cells of many plants store lipid in form of oil bodies or oleosomes, (d) Cells of petals of many eudicots contain large vacuoles for storing water soluble pigments in order to attract their pollinators, (e) Vacuoles of sepals and petals (perianth) of most monocots are not as conspicuous as in eudicots, as many of them are pollinated by wind. (*See insert for color representation of the figure*.)

microfibrils and organizes the plane of cell division. Cellulose exists in the form of crystals in the cell wall and forms microfibrils which are embedded within the cell wall. The cell wall is also crucial for cell growth and development. Structural and chemical differences in the cell wall may exist within a tissue or and even within a cell. The cell wall of roots epidermal cells may be different from the cell wall of epidermal cell of stem, leaf or flower depending upon its physiological role.

Primary cell wall is characteristic of all plants cells and is composed largely of cellulose microfibrils which are embedded in a matrix of pectin and cross-linking glycans. The matrix of the cell wall is laid down in cell plate followed by synthesis of cellulose microfibrils after the plate has reached the side of cells. However, *secondary cell wall* is characteristic of xylem tracheary elements and fibers and involves deposition of *lignin*, a phenolic compound.

Primary cell wall is composed of almost 35% of cellulose, 35% pectin and 25% hemicelluloses compounds. Cellulose is the main carbohydrate of cell wall which exists as unbranched polymer of D-glucose molecules connected by ß-1,4 glycosidic linkage. Major hemicelluloses (branched polymer) of the cell wall are xylans, glucomannans, xyloglucans and ß-D-glucans. The protein part of the cell wall includes cyclins and expansins which are important for growth and development of the cell wall.

Pectin compounds are important constituents of the cell wall which are present in *middle lamella* which is the outer cementing layer of the cell wall. Galactouronic acids connected by α-1,4-D are basic units of pectins. Incorporation of methyl groups to carboxylic groups of these units make them esterified. Their linkage with Ca^{++} and Mg^{++} makes pectic compounds insoluble, thus, limiting cell wall application in food industry. Pectic compounds like galactouronic acids, rhamnogalactouronins (RGI and II) prevent the cell wall from dehydrating, give them shape and cause expansion. However, RGII in primary cell walls exists in form of dimer cross-linked with borate. This dimer provides enough support to the cell wall for its growth.

Secondary cell wall is different from primary cell wall in having more cellulose and due to the presence of lignin. Both are attached with each other by means of covalent bonding. In addition, secondary cell wall is composed of hemicellulose and lignin which is deposited between plasma membrane and primary wall and prevents enlargement of the cell. Precursors of secondary wall synthesis like monolignols are secreted into the cell wall space and become randomly cross-linked depending upon reactive oxygen species, generated by laccases and peroxidases which makes the cell wall resistant against pathogens and also gives structural support to the cell wall. Some alcohols like coniferyl, caumaryl and sinaply groups are also part of secondary cell wall along with deposition of lignin.

Monocots are different from eudicots in many ways. Some differences also exist in the cell wall, that is, presence of different polymers type and their abundance in the cell wall, presence of SiO_2 forming phytoliths, especially cell walls of commeliinids including grasses contain relatively small amount of pectin and structural proteins. The cell walls of monocots are composed of upto 30% cellulose, 25% hemicelluloses, 30% pectin and up to 10% glycoproteins with an increased amount of ferulate in plants like wheat, maize, rice and sugarcane which are linked with glucurunoarabinoxylans (GAX) (Molinari *et al*., 2013). Furthermore, a unique feature of the cell walls of grasses includes accumulation of β-glucan in addition to GAX during their elongation.