

# *Flowering Plants*

STRUCTURE AND  
INDUSTRIAL PRODUCTS

AISHA SALEEM KHAN



WILEY



## Flowering Plants



# Flowering Plants

Structure and Industrial Products

*Aisha Saleem Khan*

*Forman Christian College  
Lahore  
Pakistan*

**WILEY**

This edition first published 2017  
© 2017 John Wiley & Sons Ltd

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

The right of Dr Aisha Saleem Khan to be identified as the author(s) of this work has been asserted in accordance with law.

*Registered Offices*

John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA  
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

*Editorial Office*

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at [www.wiley.com](http://www.wiley.com).

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

*Limit of Liability/Disclaimer of Warranty*

The publisher and the authors make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or website is referred to in this work as a citation and/or potential source of further information does not mean that the author or the publisher endorses the information the organization or website may provide or recommendations it may make. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

*Library of Congress Cataloging-in-Publication Data*

Names: Khan, Aisha Saleem, author.

Title: Flowering plants : structure and industrial products / Dr. Aisha Saleem Khan.

Description: First edition. | Hoboken, NJ : John Wiley & Sons, Inc., 2017. |

Includes bibliographical references and index.

Identifiers: LCCN 2016051233 (print) | LCCN 2016052638 (ebook) |

ISBN 9781119262770 (cloth) | ISBN 9781119262800 (pdf) | ISBN 9781119262787 (epub)

Subjects: LCSH: Angiosperms. | Angiosperms--Utilization.

Classification: LCC QK495.A1 K43 2017 (print) | LCC QK495.A1 (ebook) |

DDC 582.13--dc23

LC record available at <https://lcn.loc.gov/2016051233>

Cover image: Courtesy of the author

Cover design: Wiley

Set in 10/12pt Warnock by SPi Global, Pondicherry, India

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





## Contents

**Preface** *xv*

**Acknowledgements** *xvii*

<b>1</b>	<b>An Introduction to Flowering Plants: Monocots and Eudicots</b>	<b>1</b>
1.1	An Introduction to Major Group of Angiosperms: Monocots, Eudicots and Basal Angiosperms	1
1.2	Plant Cell: Revisions and Few Updates	5
1.2.1	A Cellulosic Cell Wall is Crucial for all Plant Cells	7
1.2.2	Plant Plasma Membrane Allows Molecules to Enter Only Through Their Respective Channels	11
1.2.3	Mitochondria Convert Energy of Glucose in ATP and in Reducing Powers	13
1.2.4	Plant Vacuoles Store Water, Pigments and Compounds of Defensive Nature	14
1.2.5	Golgi Apparatus	15
1.2.6	Nucleus Encodes Genes Required for Enzymes Forming Products of Commercial Applications	15
1.2.7	Plastids are Sites of Sugar and Fragrance Formation	16
1.2.8	Tannosomes are Chloroplast-Derived Organelles Which Contain Polymers of Tannins	17
1.2.9	Ribosomes	17
1.2.10	Endoplasmic Reticulum	17
1.2.11	Peroxisomes	18
1.2.12	Oleosomes	19
1.3	Intracellular and Extracellular Communications are Crucial for Cells' Metabolic Demands	19
1.4	Future Perspectives	22
	References	23
	Further Reading	23
<b>2</b>	<b>An Introduction to Angiosperm Natural Products</b>	<b>31</b>
2.1	Introduction	31
2.2	Glucose Serves as a Precursor for Formation of Primary and Secondary Metabolites in Plants	32
2.3	Classification of Natural Products of Angiosperms	33

- 2.3.1 Alkaloids Provide Defense Against Herbivory Due to Their Bitter Taste in Plant Organs 33
- 2.3.2 Flavonoids are Important Pollination Pigments and Increase Plants' Demands in Floriculture 35
- 2.3.3 Glycosides are Sugar-Containing Natural Products 37
- 2.3.4 Terpenoids Make Fragrances and are Used in Perfume and Cosmetic Products 39
- 2.4 Techniques for Isolation of Secondary Metabolites With Future Perspectives 44

References 46

Further Reading 47

### **3 Plant Tissues Organization of Angiosperms 53**

- 3.1 Introduction to Plant Tissues 53
- 3.2 Diversity of Plant Cell 53
- 3.3 Parenchyma is the Main Ground Tissue of Plants 55
- 3.4 Collenchyma: Introduction and Distribution 55
- 3.5 Sclerenchyma is the Mechanical Tissue of Plants 57
- 3.5.1 Fibers Types in Plants 57
- 3.5.2 Commercially Important Fibers 57
- 3.5.3 Making of Fabrics From Corn Fibers 59
- 3.5.4 Diversity in Sclereids 59
- 3.6 Vascular Tissues: Xylem and Phloem 61
- 3.6.1 Xylem 61
- 3.6.2 Why is There a Need of Water Transport? 61
- 3.6.3 Leaf Morphology and Venation 62
- 3.6.4 Tracheary Elements 63
- 3.6.5 Why Tracheids and Vessels are Water-Transporting Cells? 65
- 3.6.6 Significance of Lignification in Xylem 65
- 3.6.7 Genetic Modification of Lignin for Bioenergy Crops 65
- 3.6.8 Pits and Pit Membranes 66
- 3.6.9 Proteomic Analysis of Xylem Sap Provides Evidences of Proteins Translocation Through Xylem Sap 66
- 3.6.10 Water Channels in Plant Membranes 69
- 3.7 Phloem 69
- 3.7.1 Significance of Callose Deposition 69
- 3.7.2 Companion Cells 69
- 3.7.3 Evaluation of Phloem Sap Through Modern Techniques 71
- 3.8 Future Perspectives 72

References 72

Further Reading 73

### **4 Floral Cell Biology and Diversity in Floral Cells 77**

- 4.1 Introduction to Angiosperms Flowers: Monocots and Eudicots 77
- 4.2 Morphological & Anatomical Characteristics of Eudicot Flowers 77
- 4.2.1 Sepals Morphology and Anatomy 79

4.2.2	Petals Morphology in Response to Their Pollinators	81
4.2.3	Epidermal Cell of Petals and Elaiophores	85
4.2.4	Anatomical Characteristics of Eudicot Petals	87
4.2.5	Morphological and Anatomic Features of Carpels	87
4.2.6	Ovule Anatomy	90
4.2.7	Stamens: Morphology and Anatomy	93
4.2.8	Vascular Supply to Stamens	94
4.2.9	Stamen Anatomy and Pollen Development	94
4.3	Morphology of Monocots Flowers	95
4.3.1	<i>An Account of Economic Importance of Z. mays (Corn)</i>	96
4.4	Channels and Transporters Within Floral Cells	98
4.5	Future Perspectives	102
	References	102
	Further Reading	103

<b>5</b>	<b>Signaling During Sexual Reproduction in Angiosperms</b>	<b>107</b>
5.1	Introduction	107
5.2	Angiosperms Show Diversity in Their Sporophytic and Gametophytic Generations	108
5.3	Angiosperms Spend Most Part of Their Lives as Sporophytes and Produce Gametophytes for a Shorter Period of Time	108
5.4	Septs From Pollination to Fertilization	111
5.4.1	Stigma of Angiosperms May be Dry or Wet	111
5.4.2	Pollen Landing on Stigma (Rehydration)	119
5.4.3	Style Anatomy and Types in Angiosperms	119
5.4.4	Growth of Pollen Tube	120
5.4.5	Physiological Activities Within Pollen Tube	123
5.4.6	Cysteine Rich Proteins (CRP) Facilitate Pollen and Pistil Interaction	124
5.4.7	Steps Involved in Fertilization	124
5.4.8	Sperm Cell in Angiosperms	127
5.4.9	Molecular Basis of Reproduction	127
5.4.10	Temperature Affects Pollination	127
5.5	Future Perspectives	128
	References	128
	Further Reading	129

<b>6</b>	<b>Physiologically Active Metabolic Pathways in Floral Cells</b>	<b>135</b>
6.1	Introduction to Floral Physiology	135
6.2	Glucose Fates in Floral Cells Differ According to Their Metabolic Demands	137
6.3	PPP Provides Floral Cells With Their Nucleotides and Important Pigments	141
6.4	ATP and NADPH Produced Through Photochemical Reactions Provide Energy for Sugar Formation in Stroma of Chloroplasts	143
6.5	Floral Photosynthesis Contributes to Sugar Requirements of Floral Whorls	145

6.5.1	Presence of Stomata and Chloroplasts in Flowers Facilitate Sugar Formation	149
6.5.2	Sepals of Angiosperms have Developed Many Adaptations for Foliar Photosynthesis	150
6.5.3	Photosynthesis in Anthers is Required for Metabolic Demands of Developing Pollen Grains	150
6.5.4	Chloroplasts in Exocarp of Fruits are Modified and are Photosynthetic	151
6.6	Future Perspectives	155
	References	155
	Further Reading	156

## **7 Anthocyanins: Accumulation in Plants and Role in Industries 161**

7.1	Anthocyanins Accumulation in Different Organs Is Indicative of Their Multiple Roles	161
7.2	Anthocyanidin Biosynthesis Takes Place in Cytosol of Cells, However, They are Accumulated in Vacuoles	162
7.3	Anthocyanins Exist in Modified Forms in Cells	165
7.4	Anthocyanins Transport to Vacuoles	168
7.5	Anthocyanins Role is Dependent Upon Their Location and Accumulation	168
7.5.1	Accumulation are Defensive Pigments in Vegetative Organs	168
7.5.2	Accumulation and Role in Leaves	171
7.5.3	Anthocyanins are Involved in Senescence of Leaves	174
7.5.4	Anthocyanins as Defensive Pigments Against Insects	175
7.5.5	Anthocyanins Protect Plants Against UV Light	176
7.5.6	Role in Scavenging Reactive Molecular O <sub>2</sub>	176
7.5.7	Anthocyanins are Crucial for Pollination and Seed Dispersal in many Eudicots	176
7.5.8	Accumulation in Fruits	178
7.6	Industrial Applications of Anthocyanins	178
7.7	Future Perspectives	181
	References	182
	Further Reading	184

## **8 Carotenoids: Introduction, Classification and Industrial Uses 189**

8.1	Carotenoids are Vital for Leaves as Light Absorbing Pigments and for Flowers to Attract Their Pollinators	189
8.2	Oxygenated and De-oxygenated Carotenoids are Major Carotenoids in Angiosperms	190
8.3	Carotenoid Biosynthesis is Under the Control of Transcriptional Regulation	193
8.4	Carotenoids are Localized in Plastids in Form of Crystals and Plastoglobuli	193
8.5	Carotenoids Accumulation Takes Place in Chromoplasts of Autumn Leaves of Eudicots	197
8.6	Carotenoids Pigments in Flowers and Pollens	197
8.7	Lutein are Important Antenna and Photoprotective Pigments in Thylakoids of Chloroplasts	199

8.8	Capsaicin is a Carotenoid Derivative Which Causes Hotness of Capsicum spp.	200
8.9	Carotenoid Accumulation in Epidermal Cells of Many Fruits is Due to Conversion of Chloroplast Into Chromoplasts	202
8.10	Transcriptional Regulation of Carotenoids in Fruits	203
8.11	Application in Food, Pharmaceutical, Cosmetic, Textile and Nutraceutical Industries	203
8.12	Future Challenges	205
	References	207
	Further Reading	208
<b>9</b>	<b>Alkaloids Biosynthesis, Translocation and Industrial Products</b>	<b>213</b>
9.1	Alkaloids are Nitrogen-Containing Natural Products Which Provide Defense Against Herbivores	213
9.1.1	An Account of Historical Uses of Alkaloids	214
9.1.2	Many Alkaloids are Psychoactive Compounds and Act as Neurotransmitters	215
9.2	Alkaloids are Synthesized in Cytosol and Accumulated in Vacuoles as They are Toxic for Plant Cells	216
9.2.1	Monoterpenoids Indole Alkaloids (MIA) Derivatives are Synthesized From Tryptophan	216
9.2.2	Tropane Alkaloids are Tyrosine Derivatives	216
9.3	Purine Nucleotides Serve as Precursors of Caffeine Synthesis	219
9.4	History of Discovery of Caffeine	222
9.4.1	Caffeine is a Popular Stimulant Alkaloid in Coffee and Teas	223
9.4.2	Industrial Steps in Coffee Making Determines Their Aroma and Taste	223
9.4.3	Supercritical CO <sub>2</sub> Method is Efficient for Producing Decaffeinated Coffee	224
9.4.4	Teas are Representative of Culture, Tradition and Civilization	224
9.4.5	Black, Green and Oolong Teas	226
9.5	Theobromine is an Alkaloid Widely Used in Chocolates and Teas	227
9.5.1	Chocolate Formation: From Cacao Beans to Markets	227
9.6	Clinical Applications of Alkaloids are Due to Their Mode of Action	228
9.7	Development of Physiologically Functional Food Containing Alkaloids as Food Vaccines	230
9.7.1	Development of Transgenic Caffeine Resistant Plants	230
9.7.2	Use of Caffeine in Cosmetic Products	231
9.7.3	Alkaloids in Medicinal Products	231
9.7.4	Future Challenges for Agriculture and Cosmetic Industries	235
	References	236
	Further Reading	237
<b>10</b>	<b>Nectaries, Carnations and Ornamental Hybrid Flowers in Floriculture</b>	<b>241</b>
10.1	Introduction	241
10.2	Nectaries are Nectar Synthesizing Structures of Plants	242
10.2.1	Nectar Guides	242
10.2.2	Nectar Secretion and Important Metabolites	243
10.2.3	Molecular Basis of Nectar Secretion	245

10.3	Ornamental Transgenic Plants in Floriculture	247
10.3.1	Development of Transgenic Roses	247
10.3.2	Ornamental Hybrids in Floriculture	248
10.4	Dianthus spp. are Major Carnations in Floriculture	250
10.4.1	Economic Importance of Carnations	254
10.4.2	Genetically Modified Carnations and Ornamental Plants	254
10.5	Future Perspectives in Floriculture Industries	255
	References	255
	Further Reading	256

<b>11</b>	<b>Floral Essential Oils: Biosynthesis, Classification and Commercial Applications</b>	<b>261</b>
11.1	Fragrance Formation is a Unique and Genetically Controlled Characteristic of Many Angiosperms	261
11.2	Number of Carbon and Hydrogens Atoms in Isoprene Units Determine Their Roles in Plants	263
11.2.1	Two Isoprene Units (Monoterpenes) are Responsible for Giving Fragrances	263
11.2.2	Secretory Structures and Mechanisms Involved in Release of Essential Oils	264
11.2.3	Formation of Monoterpenoids Like Menthol is a Part of Chemical Defense of Mint and Other Plants	266
11.2.4	Linalool is a Defensive Terpenoid and a Volatile Attractant	266
11.2.5	Geraniol: A Volatile Attractant and Defensive Essential Oil in Cosmetic and Medicinal Products	270
11.3	Many Terpenoids are Insecticidal and Act as Allelochemicals	272
11.4	Sesquiterpenes are Defensive Terpenoids of Many Plants	272
11.5	Diterpenoids are Important Phytohormones Which Comprise of Four Isoprenoid Units	274
11.6	Terpenoid Biosynthesis in Plants Proceeds in Two Different Cellular Compartments	276
11.6.1	Vanillin Biosynthesis	278
11.7	Economically Important Terpenoids	278
11.7.1	Bio-engineered Terpenoids	281
11.8	Future Challenges	282
	References	282
	Further Reading	283

<b>12</b>	<b>Aromatic Molecules From Flowers in Perfume and Cosmetic Industries</b>	<b>287</b>
12.1	Introduction and Overview of Perfume and Cosmetic Industries	287
12.2	History of Perfume Making	288
12.3	Aromatic Flowers, Leaves and Woods Used in Perfumery	289
12.4	Traditional and Modern Techniques of Distillation and Isolation of Fragrant Molecules	290
12.4.1	Collection & Extraction of Essential Oils are Prerequisite Steps in Traditional Perfume Making	291
12.4.2	Enfleurage & Maceration Through Grease and Fats	291

12.4.3	Solvent Extraction Convert Aromatic Molecules in Concrete and Absolute	291
12.4.4	Eau De Parfum, Eau De Toilette and Eau De Cologne	294
12.4.5	Perfume Notes	294
12.5	CO <sub>2</sub> as a Solvent to Extract Fragrant Molecules in Super-critical CO <sub>2</sub> Fluid Extraction Method	294
12.6	Modern Perfume Making Machines	296
12.7	Aromatherapy: Relaxation Through Aromatic Molecules	296
12.8	Cosmetic Industry: An Overview and History	298
12.9	Popular Plants and Their Products in Cosmetic Products	300
12.10	Anti-Aging Properties of Some Plants and Their Applications in Cosmetic Products	301
12.11	Bioengineered Aromatic Bacteria With Lemon and Rose Fragrances	302
12.12	Future Considerations	307
	References	307
	Further Reading	308
	<b>Glossary</b>	<b>311</b>
	<b>Index</b>	<b>321</b>





## 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<sub>2</sub> 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

example, ferns, horsetails and clubmosses. 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.

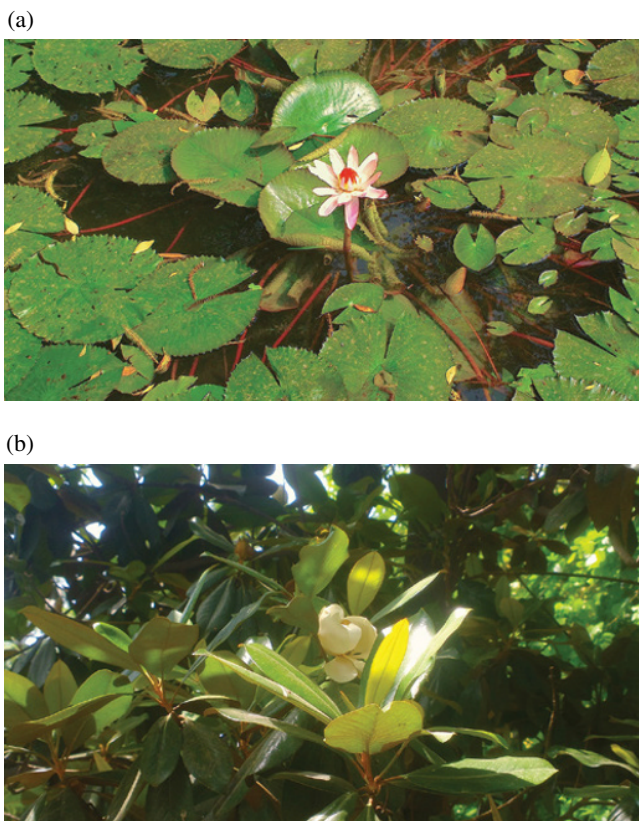
Angiosperms also known as *flowering plants* are the largest monophyletic group of seed producing plants which have evolved many efficient ways of survival over the period of time. They are unique from other group of plants due to the development of *endosperm* (nutritive tissue around embryo within 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.

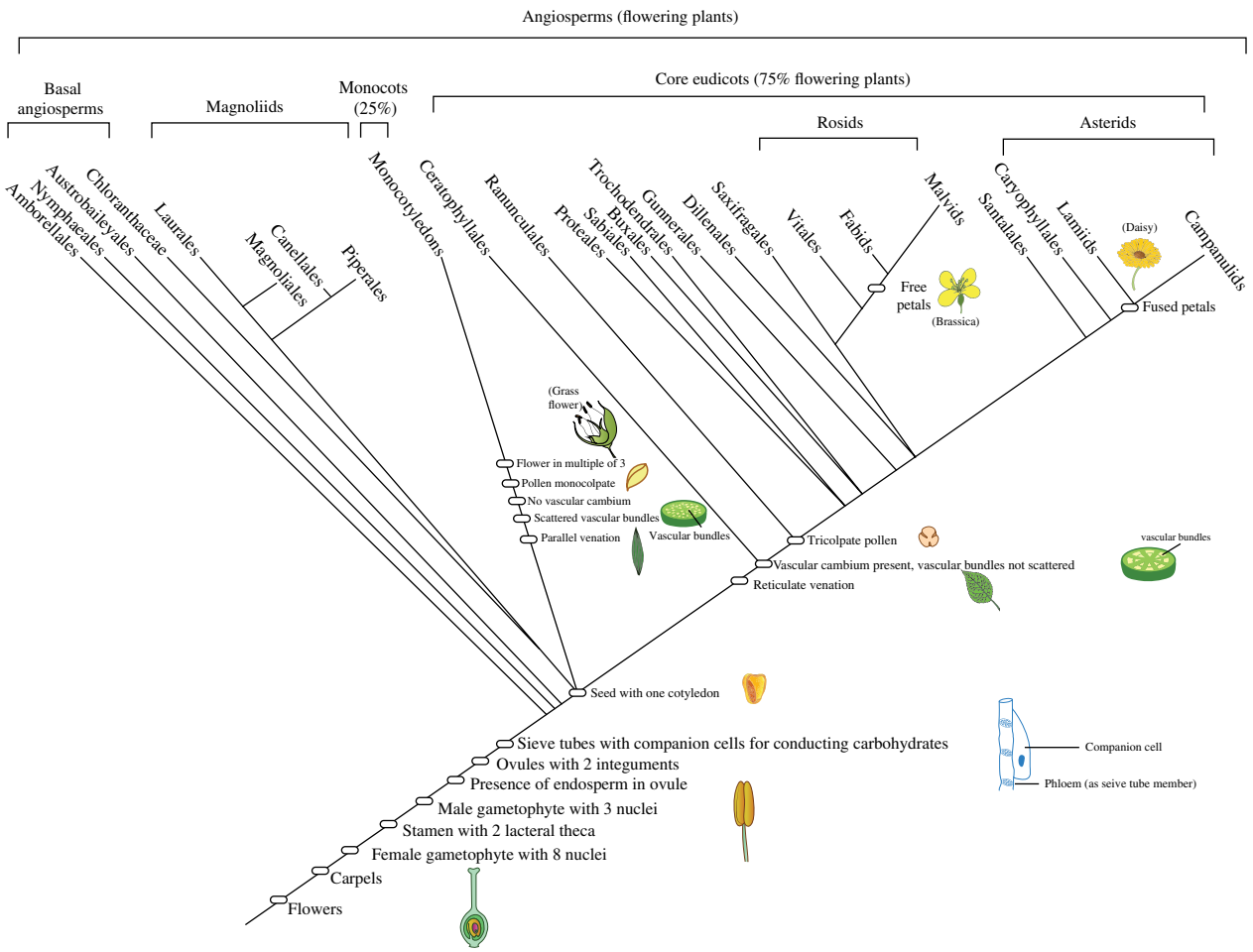
*Eudicots* also known as *true dicots*, composed of more than 75% of angiosperms and are characterized by their monophyletic origin and presence of *tricolpate* pollens (having three apertures). This group of angiosperms represents abundant clade of angiosperms. Figure 1.2 shows a cladogram of flowering 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.



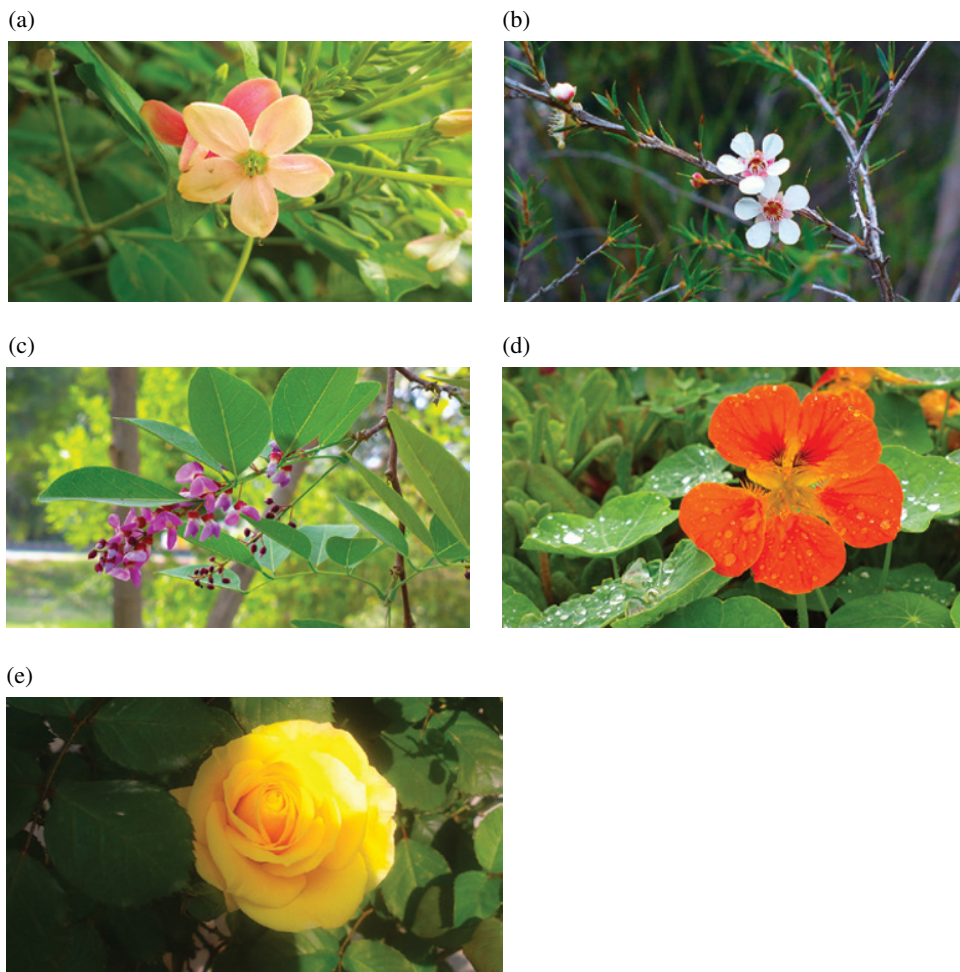
diverse clades which evolved separately are *asterids* (lamiids and campanulids) and *rosids* (fabids and malvids) (based on APG III) which are classified on the basis of their tendency to produce fused or free petals (Figures 1.3 and 1.4). Evolutionary traits, apomorphies, which are important in classification 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).





**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) *Tropaeolum 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.

(a)



(b)



(c)



(d)



**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 (*Zantedeschia 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.

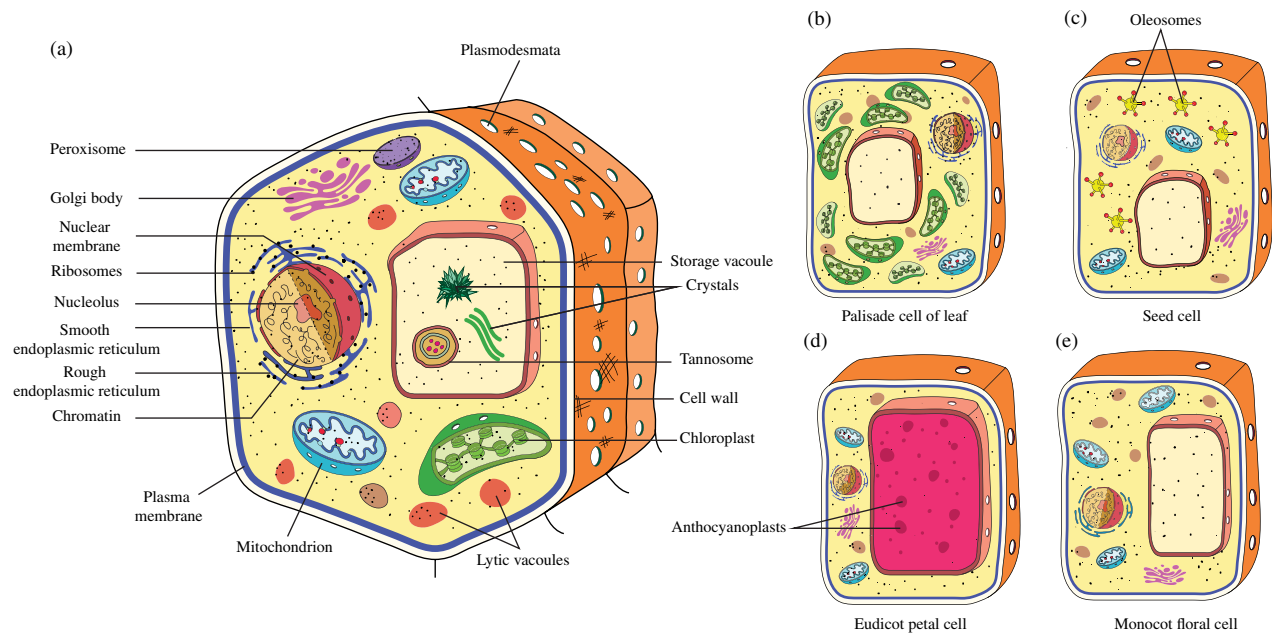
Plasma membrane encloses many membrane-bound structures, that is, *organelles* which are present within a fluid *cytosol* which is the site for main metabolic activities of cell. Main organelles which are part of almost every plant cell include nucleus, mitochondria, plastids, vacuoles, endoplasmic reticulum, 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
<b>Root</b>	Fibrous, vascular bundles are collateral	Taproot, xylem in centre
<b>Stem</b>	Soft, herbaceous with scattered vascular bundles	Soft in non-woody herbs or woody but vascular bundles are compactly arranged
	<b>Wheat (<i>Triticum aestivum</i>)</b> 	<b>Coriander (<i>Coriandrum sativum</i>)</b> 
<b>Leaf</b>	Parallel venation 	Reticulate venation 
<b>Flower</b>	Ear of wheat 	Umbel inflorescence of coriander 
<b>Fruit</b>	Wheat hull or husk 	Coriander fruit 
<b>Seed</b>	Wheat grains (monocots) 	Seeds showing two cotyledons (eudicots) 
<b>Pollination</b>	Mostly wind pollinated	Pollination through insects and animals
<b>Pollen grains</b>	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 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  $\beta$ -1,4 glycosidic linkage. Major hemicelluloses (branched polymer) of the cell wall are xylans, glucomannans, xyloglucans and  $\beta$ -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  $\alpha$ -1,4-D are basic units of pectins. Incorporation of methyl groups to carboxylic groups of these units make them esterified. Their linkage with  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  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 sinapyl 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  $\text{SiO}_2$  forming phytoliths, especially cell walls of commelinids 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 glucuronoarabinoxylans (GAX) (Molinari *et al.*, 2013). Furthermore, a unique feature of the cell walls of grasses includes accumulation of  $\beta$ -glucan in addition to GAX during their elongation.

Presence of gelatin-like properties of the cell wall which is due to *O*-acetylated of the cell wall polymers, increases its applications in food industry. However, their presence also limits their use in biofuel technology and modern research is focusing on reduction of *O*-acetylation of plants' cell wall (Gille & Pauley, 2012). In the cell walls of dicots, only side chains of galactosyl-residue in xyloglucans are *O*-acetylated, however, in monocots-like grasses glucosyl-residues of xyloglucans are *O*-acetylated.

Recent emerging trends in cell wall technology include determination, modification and isolation of cell wall polymers for use in biomaterial, pharmaceutical and food industries through techniques like NMR and mass spectrometry. Orientation of cellulose fiber in the cell wall can be determined through Raman micro spectroscopic methods in herbaceous plants (Sun *et al.*, 2016). Recently, cotton fibre is considered to be a single-cell model for cell wall and cellulose research.

The cell wall not only provides protection to the cell but also provides passages for the entry and exit of molecules in the form of pores, known as *plasmodesmata* which are extensions of smooth endoplasmic reticulum and regulate transport of molecules within range of 900 daltons. A typical plant cell may have more than 10,000 plasmodesmata on all sides of the cell wall, the exception being the outer side of epidermal cells.

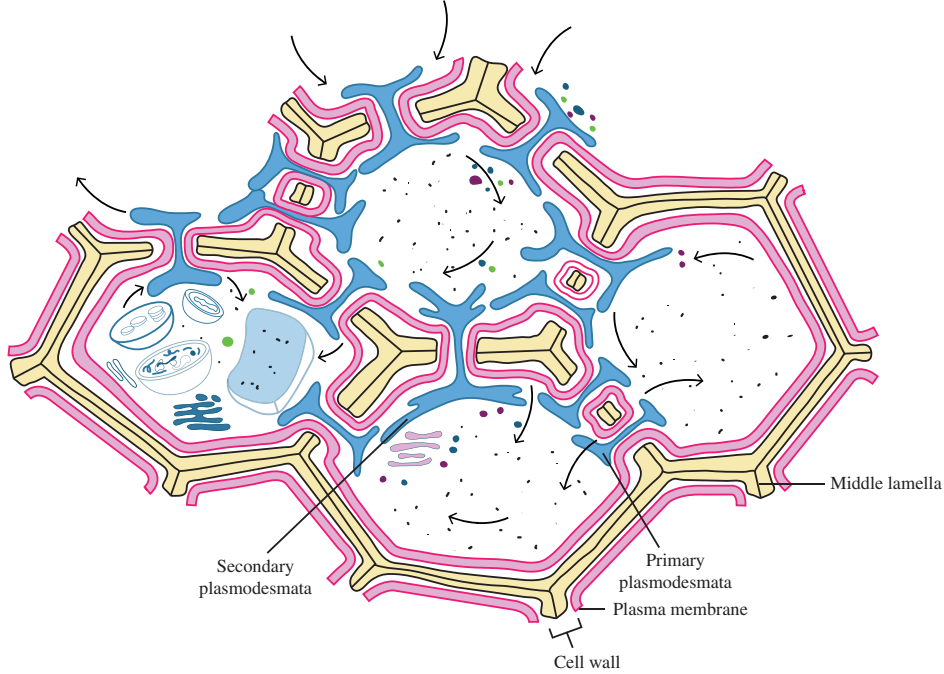
*Plasmodesmata* provide connections among cells for the transport of molecules, however, transport through plasmodesmata is not specific like cell membrane. There may be up to 1,000 to 10,000 or even more number of plasmodesmata present within a single plant cell. Plasmodesmata are of two kinds, primary and secondary. *Primary plasmodesmata* are formed during cell division. They are extensions of smooth endoplasmic reticulum in the form of tube, that is, desmotubules which are lined with plasma membrane through filamentous proteins (Figure 1.7). *Secondary plasmodesmata* are branched which develop during cell expansion. Plasmodesmata play important role during floral development and also involved in intercellular signaling especially in ovules.

### 1.2.2 Plant Plasma Membrane Allows Molecules to Enter Only Through Their Respective Channels

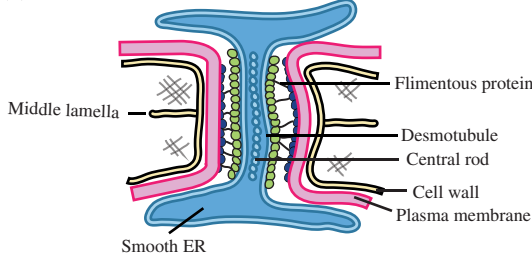
Plasma membrane is the lipid and protein part of a plant cell next to the cell wall which regulates the transport of molecules. The lipid part of membrane makes a bilayer of phospholipids which provides a barrier for transport of molecules due to its hydrophobicity. Significance of bilayer is to give support to many protein channels which are embedded within plasma membrane, and also for better trapping of molecules inside the cytosol. Non-lipid part of plasma membrane is composed of proteins which makes up to 75% of membrane and allows transport of molecules which cannot simply cross the membrane through diffusion. They include polar and large molecules like sugars or charged molecules like amino acids, nitrates, sodium, potassium, calcium, and so on. Concept of plasma membrane is just like a room, whereas proteins make the gates, where molecules will cross their respective *gates* or *channels* (Figure 1.8). Plasma membrane also regulates the movement of water molecules through aquaporins channels. Water molecules pass in a single row through this pore.

Although plasma membrane is the main membrane of cell, but organelles like mitochondria, chloroplasts, nucleus, vacuoles also have their own lipids bilayers which perform role of plasma membrane. Plant membranes also are composed of several

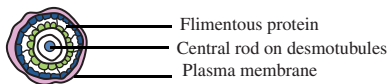
(a)



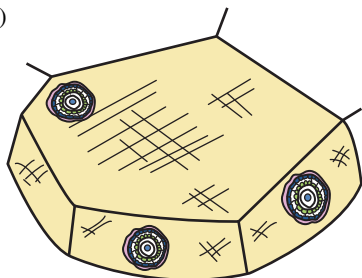
(b)



(c)

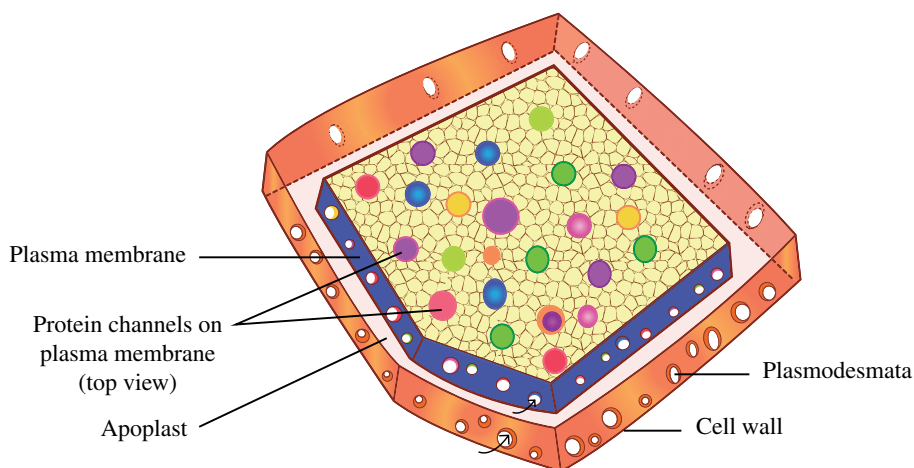


(d)



**Figure 1.7 (a-d)** (a) Plasmodesmata are extensions of smooth endoplasmic reticulum (SER) and main connections within the cell wall which allow transfer of water and other molecules from one cell to other, (b) Detailed structure of plasmodesmata showing desmotubule which extends from one cell to next through smooth ER, (c) Cross section of a desmotubule, (d) A view of plasmodesmata view within plant cell.





**Figure 1.8** Plasma membrane of plant cells is enclosed in the cell wall which surrounds it from all sides (top view). Round circles on plasma membrane represent proteins which provide passage for regulation through plasma membrane. Gaps in the cell wall indicate plasmodesmata.

sterols, for example, sitosterols, stigmasterol being the most abundant one. However, membrane sterol composition is dependent upon ecophysiological conditions involved in growth and development.

### 1.2.3 Mitochondria Convert Energy of Glucose in ATP and in Reducing Powers

Mitochondria are the site of cellular respiration and synthesize energy in the form of ATP for various metabolic needs of cells. Mitochondria multiply by division and are maternally inherited.

Mitochondria have two membranes, outer and inner which are made up of phospholipid bilayers. However, outer membrane of mitochondria comprises mostly lipids, whereas the inner membrane contains almost equal amount of lipids as well as proteins. The inner membrane is folded to increase surface area for metabolic processes like the electron transport chain and these invaginations are known as *cristae*. Outer membrane of mitochondria have proteins, that is, porins through which they communicate with the cytosol of cell and allow transfer of molecule upto 10KD, such as glucose and many ions. However, inner membrane is more permeable to molecules like  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  having pores for transport of molecules like ATP, ADP and pyruvate. Many proteins which are required for metabolic activities of mitochondria are carried through binding with receptor in an energy-dependent transport.

Space between two membranes is *inter membrane space* and fluid part of mitochondrion within *cristae* is known as mitochondrial *matrix* which is site of many processes that are crucial for providing energy to the cell. Products from glucose breakdown are transported to mitochondria for further breakdown in order to release energy.

Mitochondria have their own DNA which is present in form of loops similar to bacterial DNA. It is present in multiple copies in matrix along with ribosomes. However, mitochondrial genome encodes only a few proteins, most of them are encoded in the

nucleus. Mitochondrial genome of plants is larger in plants as compared with humans, and its size varies among different plants as in *Arabidopsis* it is 20 times larger, whereas in melon it is 140 times higher than in humans.

Mitochondria synthesize energy in the form of ATP (adenosine triphosphate), therefore, protein channels in membranes allow for transfer of ADP (adenosine diphosphate),  $P_i$  and ATP (also known as ATP and ADP *translocators*). ATP formation is immediately followed by its export through translocators to other organelles or cytosol of cell wherever energy is required within cell. ATP and ADP transport is important for cell as many processes, such as DNA replication, transcription, formation of larger molecules, translation, secondary metabolite formation and cell division are all dependent upon the availability of ATP. Therefore, mitochondria also accumulate near the site where energy demand is high in germinating pollen grain.

Mitochondria also play role in cell adaptation to abiotic stress and regulate metabolism of proteins which regulate homeostasis and are involved in programmed cell death. They are also source of providing energy to rapidly growing pollen tube cells.

#### 1.2.4 Plant Vacuoles Store Water, Pigments and Compounds of Defensive Nature

Vacuole of plant cells serve as lytic and storage compartment, which maintains turgor and homeostasis under stress conditions. *Storage* vacuoles store water, pigments, nutrients, crystals, starch, protein bodies for the plant cell and also involved in growth of cell and also help in signaling. Molecules like calcium, sodium, potassium, magnesium, chloride, nitrate and water are stored in vacuoles and help increase in height and surface area. Calcium and potassium are required for many processes within plant cells, therefore, vacuoles serve to store them and facilitate their transport within the cell. Vacuoles have many enzymes which convert toxic products into non-toxic forms. Therefore, they also detoxify harmful products like xenobiotics, as revealed by experimental techniques involving isolation of vacuoles and through replacement of vacuolar content and mutants of vacuoles.

Just like membranes of many other organelles, vacuolar membrane or *tonoplast* is also a lipid bilayer with protein transporters. Vacuoles of floral cells occupy more parts of cell as they store pigments for pollination. They also modulate turgor during growth. Vacuoles also digest old organelles due to hydrolytic enzymes which are no longer required by cells and are therefore known as *lytic* vacuoles. Mitochondria are transferred to vacuoles by endocytosis.

Aquaporins were first discovered in the vacuolar membrane of seeds so named r-TIP (tonoplast intrinsic proteins). Vacuoles of many pollens are elongated and tubular in shape. In the petals of many flowers, sometimes vacuoles of neighbouring cells store different shades of pigments within the same petal, which differentiates it from the rest of petal, thus making contrasting patterns known as a *nectar guide* which serve as a guide for pollinators.

Vacuolar pH is important factor in determining the color of flowers as an increase in pH may give the blue shade in morning glory (Yagamuchi *et al.*, 2001). This increase in pH is due to an active transport of  $Na^+/K^+$  from cytosol into the vacuole with the help of  $Na^+/K^+$  pump. Vacuoles of epidermal cells store pigments like anthocyanin which protect them against UV radiations. Tonoplast of vacuoles storing anthocyanins pigments require transporters like *ATP binding cassettes* (ABC). Vacuoles, like protein-storing

vacuoles, transfer nutrients to germinating seeds and main source of storing nutrients like Ca, Fe, Mg, P and Zn, thereby serving important role in nutrition. Vacuoles of all plants are composed of H<sup>+</sup>-ATPase, V-PPase and TIP, such as aquaporins which may differ in their role depending upon their location.

Plants vacuoles are also the site for storage of industrially important products like alkaloids and anthocyanins which are widely used in textile and food industries and are reported to have anti-cancerous properties. *Anthocyanins* are known to accumulate in pigmented structures within vacuoles known as *anthocyanoplasts* in plants like red cabbage, which may also contain enzymes for anthocyanins biosynthesis.

Channels like H<sup>+</sup>-antiports, electrogenic uniport ion and ABC transporters facilitate transfer and accumulation of secondary metabolites in vacuoles. Two proton pumps on vacuolar membrane, that is, V-ATPases and V-PPases develop gradient across tonoplast membrane. Vacuoles are crucial for storage of plants' defensive compounds in order to prevent toxicity to the rest of the cell. They are also important for synthesis of saponarin which is inhibited without vacuoles (Marinova *et al.*, 2007). New technologists have developed to express economically important proteins in plants which accumulate in vacuoles and can further be used for cultivation of plants so large number of proteins can be produced at low costs.

### 1.2.5 Golgi Apparatus

It is involved in the modification of carbohydrates and proteins, and also transports them within the cell wherever they are needed in the form of vesicles. Golgi apparatus also modifies many proteins which are involved in pollination and fertilization processes within different floral cells. Within a plant cell, it constitutes a system of stacks of thin vesicles that are held together either in a flat or in a curved array. Individual stacks of cisternae that are filled with fluid with modification are present almost all over the cytosol within plant cell.

Golgi complex coordinates with endoplasmic reticulum, and form vesicles, that fuse and form a wider thin vesicle *cisternae*. Vesicles formed by smooth ER form cisterna on *cis* face of Golgi apparatus, however, at the *trans* face, vesicles are released or carried to their destination. These vesicles may move to plasma membrane and discharge their contents. Golgi bodies are also involved in forming cell wall machinery through the same process.

### 1.2.6 Nucleus Encodes Genes Required for Enzymes Forming Products of Commercial Applications

Nucleus is an important organelle due to the presence of nucleic acids DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). DNA is main heredity material which is present on genes present on chromosomes which are thread-like structures. RNA synthesizes proteins for plants growth and metabolism through a process which we call *gene expression*.

All cells of plants possess their own nuclei. However, sieve cells of phloem loss their nuclei upon maturity and they are assisted by companion cells. Nucleus communicates with other organelles and cytosol by means of pores within nuclear membrane. Nuclear envelope is similar to plasma membrane and comprise of phospholipids as dominating lipids. Proteins which are part of nuclear membrane, facilitate transport of molecules and allow mRNA to leave the nucleus through nuclear pore. They also provide passage

for transport of molecules like ATP from mitochondria within the nucleus to energize energy-dependent reactions like DNA and RNA synthesis. *Nucleotides* which are building blocks of DNA and made up of repeating units of sugar, phosphoric acid and nitrogenous bases that are synthesized within the cytosol of the cell. Four nitrogenous bases, adenine (A), guanine (G), cytosine (C) and thymine (T) exist in a pair attached by means of hydrogen bonds. Adenine and guanine form double hydrogen bonds within the centre of double helical structure. However, guanine and thymine are attached by means of three hydrogen bonds. In RNA, instead of thymine, uracil is present. Nucleus encodes genes for formation of enzymes which are involved in pathways which leads to the formation of products of industrial importance.

### 1.2.7 Plastids are Sites of Sugar and Fragrance Formation

**Plastids** are double membrane organelles derived from proplastids, which are undifferentiated plastids in meristematic cells of root and stem. Detailed sequence analysis of genes have revealed that all plastids are evolved from a single ancestral source and thought to be originated by the engulfing of a photosynthetic organism by a non-photosynthetic organism. Like mitochondria, they multiply by division and have maternal inheritance. Plastids possess their own circular genome known as ctDNA (circular DNA) or ptDNA (plastid DNA) which is 120-160kbp in size and makes up to 0.1% of the size of a nuclear genome. Many enzymes like DNA polymerase, helicase and primase have been purified from them. Angiosperms plastids possess both plastid-encoded and nuclear-encoded RNA polymerases (Sato *et al.*, 2003). During cell differentiation, they either differentiate into chloroplasts, chromoplasts or leucoplasts. *Leucoplasts* are colorless organelles which synthesize lipids and store starch in roots, tubers or seeds.

**Chloroplasts** arise from differentiation of proplastids. They possess their own circular chromosome and enzymes for gene duplication, gene expression and protein synthesis, however, majority of proteins are encoded in nucleus and later transported to chloroplasts. Chloroplasts are known to be evolved from cyanobacteria because their genome is similar to prokaryotic genome.

Chloroplasts are one of the most abundant plastids which are present in leaves of green plants. Their presence in any organ of plant is indicative of their role in formation of sugar through photosynthesis. They contain a lipid bilayer similar to other membranes, however, glycolipids are more common in a chloroplast membrane. Chloroplast lipids like monogalactosyl diacylglycerols (MGDG) are in fact one of the most abundant lipids on our planet. The membrane of chloroplast is composed of pores which facilitate exchange of molecules and allow them to communicate with the cytosol of cell. Porins in outer membrane of chloroplasts are non-specific and allow transfer of molecule upto 3 nm in size. However, the inner membrane is composed of specific protein translocators which allow transfer of molecules between the cytosol and stroma.

Pigments which are involved in photosynthesis, that is, antenna pigments which are embedded in the lipid membranes of thylakoids which are disc shaped structures. A pile of thylakoids make *grana* which are interconnected through lamellae within chloroplasts. All angiosperms possess chlorophyll *a* as necessary pigments which are crucial for light reactions, however, other pigments, that is, chlorophyll 'b', carotenes and luteins, are also present on thylakoid membranes and transfer energy of

sunlight to chlorophyll *a*. Fluid of chloroplast is known as *stroma* which contains starch grains, free ribosomes and enzymes for formation of carbohydrates during the Calvin cycle. Energy molecules like ATP and NADPH are synthesized through a series of photochemical reactions on thylakoids which diffuse in the stroma to provide energy for sugar synthesis. ATP and ADP translocators are present in the inner membrane of the chloroplast envelope. *Plastoglobuli* are oil containing bodies which are found within plastids of senescing leaves.

**Chromoplasts** are usually present in the petals of flowers giving red, organ and yellow shades. They have an undulated system of membranes without grana. They contain pigments either on the membrane or in the form of plastoglobuli as droplets. During fruit ripening, many chloroplasts are converted into chromoplasts due to the formation of lipid pigments which is evident through a change of color in many fruits like tomato, organ, mango, and so on. They are green when unripened, and turn into chromoplasts when mature. Plastids without pigments and lipids are leucoplasts, they are colorless plastids like amyloplasts. The white color of petals of many flowers is due to leucoplasts. *Carotenoids* are lipid-soluble pigments having 40 carbon atoms which accumulate in chromoplasts and give them that orange, yellow and red color to attract pollinators. However, the presence of carotenes in the chloroplast protects antenna pigments against high intensities of light and helps in the absorption of energy for photosynthesis.

### 1.2.8 Tannosomes are Chloroplast-Derived Organelles Which Contain Polymers of Tannins

Plants synthesize many molecules in response to the defense against pathogens and herbivores. Proanthocyanidins are type of flavonoids which are also known as *condensed tannins*. They play a defensive role against pathogens and UV radiation. Although tannins inclusions are previously reported to be synthesized by endoplasmic reticulum, recent ultrastructure studies revealed that they are derived from chloroplasts (Brillouet *et al.*, 2013). Figure 1.9 shows developmental stages in the differentiation of chloroplast into *tannosomes* (tannin-containing organelles) which involves unstacking and inflation of thylakoids grana forming tannosomes, which are later encapsulated and transferred as shuttle from cytosol to vacuoles where they are stored in order to protect the rest of the cell from toxic effects of tannins.

### 1.2.9 Ribosomes

are the site for protein synthesis. They are membrane-bounded structures and consist of one large and one smaller subunit. However, the number of ribosomes depends upon the function of cell where they are present. Plant cells contain fewer ribosomes than animal cells. However, the cells of seeds in legumes contain large numbers of ribosomes.

### 1.2.10 Endoplasmic Reticulum

(ER) forms part of the endomembrane system and communicates with the nuclear envelope. It is a system of flattened membrane, sacks and tubules. ER without ribosomes is smooth endoplasmic reticulum (SER), whereas ER with ribosomes is rough