Sudhir Sopory *Editor*

Sensory Biology of Plants

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Foreword

It is a great pleasure to write this Foreword for this volume edited by my former pupil Professor Sudhir Sopory, who came to my laboratory for work toward his doctoral degree back in the late 1960s. Not all teachers have the longevity and good fortune of seeing their former pupils grow for such a long period – I am 86 now. Sudhir Sopory was among the founding group after I returned from Caltech in the early 1960s. I was member of the faculty of a department at the University of Delhi whose beginning is intimately linked with the British Raj and the Empire and which greatly benefited by the direct attention given by the imperial government during the 1930s and 1940s. (If I can expand a bit, it so happens the main building of the University of Delhi, an iconic structure, was indeed originally the Viceroy's residence and the surrounding campus the Viceregal Estate – but later as the new capital, New Delhi got ready in the early 1930s, the Majesty's Government decided to give over the old lodge and the surrounding estate to start the University of Delhi.) Thus, it has been a privilege to pass most of my active life in this historic spot not only for me but also of Sudhir while he finished his Ph.D. But around the time he got his degree, University of Delhi had already gotten too big and crowded and the Government of India took the decision to set up the new Jawaharlal Nehru University (JNU). Sudhir was recruited as a member of the new Life Sciences School. Being in the same metropolis, it was possible for me to maintain regular contact and watch him gradually become one of India's topmost plant biologists.

After my own superannuation, I moved to the International Centre for Genetic Engineering and Biotechnology (ICGEB) in New Delhi as an Honorary Guest Scientist. By a happy coincidence, Sudhir too moved from JNU to the ICGEB as Head of the Plant Molecular Biology group, giving us an opportunity to maintain even closer contact for nearly a decade. Sudhir has not only been a keen researcher but also a great scholar. For many years, we took our lunch together. Certainly in his younger days, I may have taught him a few things, but I think I benefited more by our daily meetings. I have been in Jaipur for a decade now, but happily Sopory has maintained a regular contact. It was my good fortune to have had many talented students. But he has been unique in many ways, both academically and as a person.

Sudhir had returned to JNU for a brief span as a Vice Chancellor. But I am happy that the higher authorities in Trieste decided to bring him back to ICGEB as an Arturo Falaschi Emeritus Scientist and utilize his knowledge and experience. I think

ICGEB made a wise choice in commemorating the memory of this outstanding investigator, Prof. Falaschi, late former Director General of ICGEB. Sudhir Sopory has had wide interests. In his lectures and writings, he always had a new way of looking at things. Turning to this book, the truth is in a sense that all of modern physiology biochemistry is signaling. Though the widespread use of this word is recent, research on signaling has been going on for a long time. In the last century, when Charles and Francis Darwin were doing their classic studies on phototropism, they were in fact studying signaling. Such was also the case with Boysen Jensen, Frits Went, and two of my own gurus and grand gurus, namely, James Bonner and Kenneth Thimann (both began their careers at Caltech but Thimann had moved to Harvard in 1935). However, signaling came to have special focus and meaning when Earl Sutherland discovered the first second messenger, cyclic AMP, for which he was awarded a Nobel Prize in 1971. In my view, the work by F Jacob and J Monod also propelled research in the area greatly through development of key concepts of allostery and bringing in a new area of biochemistry of regulation. Many other key discoveries followed, such as those of transmembrane receptors, protein kinases, and G proteins and even signaling cascades were found that penetrated the nucleus and turned genes on or off. Indeed through an entire century, a string of Nobel Prizes were awarded (from Bayliss and Starling and F Banting and McLeod in the early period to more modern investigators like Cohen and Levi-Montalcini, Fischer and Krebs, and Lifkowitz) resulting in the establishment, so to say in its own right, of the new discipline in the 1980s. It is indeed then that the first reviews with the term “signaling” or “signal transduction” in their titles were published. Signaling had come to age and in 1982 came the first exclusive volume on the subject published by Elsevier.

Prof. Sopory has been interested in signaling for a long time. In 2002, he organized the first international symposium in India on *Signal Transduction in Plants* (the contributions are already published in a volume, of which, I and Ralf Oelmuller were Co-editors with him). By editing this new volume, he has brought to focus a lot of advances that have taken place since then and reaffirmed the centrality of signaling in plant biology. Largely, this volume is a product of contributions of his many collaborators and mentors, with whom he worked in India and abroad, and his students who had worked in foreign laboratories and are now working in various Institutes in India and the USA. He had a talented group of researchers, and leading the list of contributions (by his former associates) is an article by Rameshwar Sharma, who has made many outstanding contributions to photobiology of plants. Many other contributions come from the alumni or members of the Departments of Botany and Plant Molecular Biology of University of Delhi, National Institute of Plant Genome Research, JNU, and ICGEB. But there are also articles from other investigators from institutions in India and abroad (four articles are from the USA, one each from Israel, Canada, Korea, and Germany). Professor Sopory has had excellent links with all of them, and to my mind, his meticulous planning is bringing to light the influence of a whole variety of factors affecting plants in a coherent manner. The volume ends with two intriguing titles (the last one with an Indian view on plant life). I am sure there will be some surprise for us all. Once again, my sincere admiration for this valuable enterprise.

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[1] Prof. S.C. Maheshwari passed away on June 12, 2019

Preface

All life on this planet is dependent on plants for their survival. The life story of a plant in the form of a poem by a class 7 student (my granddaughter) is given in Box I, and the views of Nobel laureate Rabindranath Tagore on life of trees and on Sir J.C. Bose, who first showed the sensory nature of plants, are given in Box II. Since the time of Bose, amazing advancements have been made to understand the physiological, biochemical, and molecular aspects of plant growth and development and responses of plants to external environment. During the course of evolution, as new plant forms evolved, they also developed sensory perceptions and mechanisms to decide the best ecosystem for them to adapt to their new home and accordingly developed good relationships with soil, climate, insects, and other plants around. One thing that is becoming clear from lot of new research is that plants respond efficiently to the changes in the environment, regulate necessary biochemical and molecular machinery, and process the input information for their development and survival. It is this aspect of plant sensory biology that we are partly covering in this volume. Each chapter presents scientific evidence and knowledge that have accumulated, with cited references, to communicate the sentient nature of plants and to reveal how plants perceive physical and biological environment around them and respond accordingly.

Chapter 1 deals with plant diversity and adaptation during the evolution of plant life, as it moved from the aquatic to the terrestrial environments. Following this broad overview, the chapters in this volume have been categorized under three parts.

Part I is on the awareness of plants to the external environment. There are six chapters in this section which deal with the present state of knowledge on perception and responses of plants to light and darkness, to various nutrients, and to water. Other aspects such as how plants respond to gravity, sound, and touch, and also about variations in conditions that are perceived by plants as stress environment, are also covered in this section as separate chapters.

Part II discusses about the plant cellular machinery, both chemical and molecular, and the mechanisms thereof, for decoding and transmitting external information and cues. The broader questions are the following: What molecular machinery is functioning in plants? What are the various chemicals and hormones that are used by plants to regulate their inner self following perception of changes in the environment? This is needed for their proper growth and development both under normal

Box I Excerpts from Poem "Plant"
by Dhriti Medigeshi Class VII

It all started as a sapling
Every plant, every flower, every tree
But before it was a sapling
It was a tiny little seed

Tucked into the soil
Living on water and sunlight
Waiting to see the world
With tremendous delight

Summer went
And then came monsoon
It rained all day
All night and afternoon

The little seed
Quenched its thirst
And felt like
It would burst

The next day
Popped a tiny root
The day after that
You could see the shoot

Days after that
The stem could be seen
With leaves peeking
Out From between

A plant is a Mathematician
And a scientist altogether
Well, you just don't know
A plant is very clever

It knows chemistry
Biology and physics
It can also perform
Magic tricks

(continued)

It knows many
Complicated processes
The one it performs
Is photosynthesis

The leaves take up
The energy of the sun
And then their job
Has just begun

After doing
A lot of chores
It makes food
Called glucose

The stem acts
As a transporter
And takes the food
From one part to another

A plant stores its food
In leaves, stems and roots
And sometimes it's also
Present in a fruit

A fruit comes from
A colourful flower
That's what you call
Flower power

Box II Tagore on Trees
Sushanta Dattagupta

Rabindranath Tagore – though universally acclaimed as a poet, philosopher, and lyricist – was an avid lover of science. In a book in Bengali on science, called *Visva Parichay* (*Introduction to the Universe*) [1], he had written in 1934:

Any educated person must enter the arena of science if not the core of science, and in this regard, it is no shame to take the help of literature…. I am not a serious student of science but I had this endless temptation for tasting the nectar of science from my very childhood….

(continued)

Tagore's views on science are completely enmeshed in nature and natural phenomena, as revealed in the famous dialogue with Albert Einstein, through the years of 1926–1930 [2]. In this context, trees and forests occupied a significantly large space in his mind. On this, Tagore had written in a letter to C. F. Andrews in April 1921: "…The environment in which the Aryan immigrants found themselves in India was that of the forest. The forest, unlike the desert or rock or the sea, is living, it gives shelter and nourishment to life. In such a surrounding the ancient forest dwellers of India realised the spirit of harmony with the universe, and emphasized in their mind the monastic aspect of truth…." [3]. On his concern for the environment Tagore had written in details in *Visva Parichay*.

On the importance of the tree and its relevance to the climate, Tagore wrote:

As the earth began the process of freezing into a solid lump from a liquid mass at the time of its inception its surroundings were filled with humid vapour and carbon-related gases. Further cooling led to nitrogen and other gases. It is surprising at first sight that so much oxygen had survived even though the latter is highly reactive and prone to form compounds. The reason is the abundance of trees and vegetation. The trees help imbibe carbon from atmospheric carbon dioxide to form cells and release oxygen. The resultant loss of carbon dioxide is replenished from the exhaled air of living and nonliving ones. It is surmised that life began from the semblance of oxygen left behind in ancient vegetation. The growth of the latter released further oxygen gas in the atmosphere at the expense of carbon dioxide…. The molecule called chlorophyll is present in green leaves which store sunlight in the form of energy. This energy helps create food in the form of fruits, crops, etc. On the other hand, the tiny presence of carbon dioxide in the air penetrates as carbon in vegetables, from which coal is produced, thereby aiding sustenance to life. It is the tree that is central to the food production in the form of rice and wheat through the process of mixing carbon dioxide with water with the aid of chlorophyll that draws energy from the sunlight.

It is no wonder then that Rabindranath wholeheartedly embraced and lauded the scientific achievements of his close friend Jagadish Chandra Bose in the area of plants and plant physiology. These two great sons of India were similar in age: Bose was born on 30 November 1858 and Tagore on 7 May 1861. They had other common threads – both were inheritors of emancipated and affluent "Brahmo" families of what is known as Bengal Renaissance.

In a tribute to Bose, Tagore had said [4]: "… in the prime of my youth I was strangely attracted by the personality of this remarkable man and found his mind sensitively alert in the poetical atmosphere of enjoyment which

(continued)

belonged to me. At that time he was busy detecting in the behaviour of the non-living some hidden impulses of life. This aroused a keen enthusiasm in me who had ever been familiar with the utterance of Upanishad which proclaims that whatever there is in nature vibrates with life. He had then shifted his enquiries from physics to the biological realm of plants. With the marvellously sensitive instruments that he had invented he magnified the inaudible whisperings of vegetable life, which seemed to him similar in language to the message of our own nerves. My mind was overcome with joy in the idea of the unity of the heartbeats of the universe, and I felt sure that the pulsating light that palpitates in the stars has its electric kinship in the life that throbs in my own veins…."

On 30 November 1928, Tagore had dedicated a remarkable poem in Bengali, "Vano-Vani" (The Voice of the Forest), to J. C. Bose, on his 17th birthday, which aptly captured Bose's scientific discovery [5]. We translate that poem in parts, separately highlighting the scientific content.

On photosynthesis:

Day in and day out light strikes the leaves,
to arouse the excited molecules into a
silent, rhythmic and melodious vibration;
The trees sing muted paeans to the Sun at dawn.

On the evolution of trees and Bose's path-breaking contribution:

Years and years ago our mother earth was an
arid, dreary and inert desert;
Slowly and apprehensively tree made its
appearance bringing-in the joy of life;
It had to expectantly wait through ages
to hear the footsteps of man;
Came human beings whom the tree
provided shelter and nourishment;
Primitive life was hidden in its interior that
did not find ample expression through its
pulsating leaves.
It is YOU who delightfully awakened yourself
to align your creative mind to the unravelling
of the secret of life within plants.
The primordial message of life was aroused in
grassy fields and forests but stayed unspoken.
It is YOU the great sage endowed the mute with speech,
heard the pathos of the jungle from your solitude.

(continued)

In one of the numerous letters that Tagore wrote to Bose [4], he had lightheartedly referred to Bose's experiments on plant response to external pulses – on 21 May 1901 – from Shelaidaha, thus:

I feel proud to read about the method you have discovered to pinch every aspect of nature. Until now, inanimate objects were troubling us – now I can contemplate revenge on them, thanks to your discovery. Go ahead and administer unending pinches and poisons to them – don't leave them alone. From now on Judges can pronounce 'Pinching Punishments' for inanimate objects if they ever come up for courtroom trials….

∗Senior Scientist of the Indian National Science Academy at the Bose Institute, Kolkata; also at the Tagore Centre for Natural Sciences and Philosophy, Rabindratirtha, New Town, Kolkata; (electronic address: sushantad@gmail.com); all entries in italics are author's translation from Tagore's Bengali writings, some of which are reproduced from [2], cited below

[1] Rabindranath Tagore, *Visva Parichay*, 1934, Visva-Bharati Publications, Granthan Vibhag, Kolkata
[2] Sushanta Dattagupta, *A Random Walk in Santiniketan Ashram*, 2016, Niyogi Books, New Delhi
[3] The Archives of Rabindra Bhavan, Visva-Bharati, Santiniketan
[4] Acharya J. C. Bose – A Scientist and a Dreamer 1997, Bose Institute Publication Section, Kolkata
[5] Rabindranath Tagore, in "Chitthi-Patra," Republished by Granthan Vibhag, Visva-Bharati, Kolkata, 2015

situation and also when plants face stress conditions. There are nine chapters under this section. Two of these deal with membrane-associated transducers, namely trimeric G-proteins, two-component systems, and others, and describe the role of chemical signalling. For this latter part, we have chosen to discuss about the involvement of plant hormones, calcium, nitric oxide, and reactive oxygen species (ROS). Furthermore, plants have also developed ways to sense sugars and use them to transduce signals in consonance with hormones, which is covered in one chapter. In addition, the role of an energy molecule ATP in signalling has also been discussed in another chapter where a comparison of this has been made with animal signalling. Interestingly, plants have even been shown to produce neurotransmitters which can also monitor changes in the environment and accordingly regulate plant development. This aspect is also covered in one of the chapters included in this section.

Part III deals with various plant communication systems and also how plants integrate various signals. Plants, unlike animal systems, have a cell wall. The role of cell wall in mediating external cues and regulating internal cell communications is presented in one chapter. In plants, the genetic information resides, other than in nucleus, in chloroplasts as well. A chapter deals with this aspect of communication and signalling among different organelles, especially plastids, to define how retrograde signalling between chloroplast and nucleus regulates gene expression. Furthermore, two chapters in this section deal with the communication systems. One is about the electrical signalling and long-distance communication, and the other is on how plants respond to attack from pathogens. Finally, a chapter summarizes, with a few case studies, the concept of how different cues are integrated in a coherent manner within plant cells to take decisions about their growth and survival under ever-changing environmental conditions of light, temperature, nutrients, etc.

Part IV deals with the end of the plant life and a few views on plant cognitions. There is a chapter that deals with plant cell death. Like all living organisms, plant life also comes to an end, though there are large variations in the life span in plants. From a few days, like in *Arabidopsis*, for this reason and also due to its small genome size, it has become the most sought-after model plant to trees which live for hundreds of years. The mechanism of cell and organ death as compared to the death of the plant itself is also presented.

One of the philosophical questions which have been discussed by some is as follows: Do plants have "consciousness"? A non-human type! We have attempted to compile a chapter on this with views and logic of different authors, as also the views of various theologists and spiritualists on plant life. Experiments of J.C. Bose, and those of other recent workers on the use of anaesthesia and also the work on plant memory, more specifically stress memory, are covered in this chapter.

Lastly, a commentary of a young artist, a dancer who takes inspiration from plants and innovates her dance choreography, has been included as a separate chapter on the Indian view of the natural and plant world.

One of the reasons for me to edit this book, rather than writing it solely by myself, is to acknowledge the support of my students, colleagues, and all those in whose laboratory I had worked at some time or the other during my career, coauthoring publications with them. It was nice to share my ideas and literature with some of them. This enabled me to learn a lot during the process of compilation and editing. I am also thankful to many other students who could not be a part of this project. In addition, there are a few chapters which are authored by those whom I have known but have not had any direct collaboration with them. The topics that they have covered were important for this volume, and hence, I extended an invitation to them which they kindly accepted.

I am aware that the topic of this book is rather vast. Moreover, a lot of new information is also pouring in, on daily basis, especially on various modes of plant communication, both above and below grounds and with other organisms (see some suggested readings). Nevertheless, I am hopeful that this volume will be useful to the students of plant biology and will encourage them to unravel the mysteries of plant life and further investigate how plants interact with environment and other biological species and survive successfully in their ecosystem.

Suggested Readings

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Wohllebeen P (2016) The hidden life of trees. Greystone Books Ltd., Vancouver. ISBN 978-1-77164-248-4

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I acknowledge my Ph.D. Supervisor Prof. Satish Maheshwari for encouraging me to take up research in the area of photomorphogenesis, biochemistry, and molecular biology in the early 1970s when not many plant laboratories had initiated any work in these directions in India. All through my career, I received support from my colleagues at Jawaharlal Nehru University (JNU) and at the International Centre for Genetic Engineering and Biotechnology (ICGEB), New Delhi. I am thankful to my students and collaborators in India and abroad for enriching my knowledge and expertise and agreeing to participate in this project by contributing their chapter.

My heart goes to my family, especially my wife, Meena Sopory, who in all these 45 years of our married life never demanded even an hour for herself and let me spend my time in the laboratory and library or even to undertake long sabbaticals for going abroad. I remain indebted to her for the encouragement and support all through.

A word of thanks to my aunt Prabha Devi, disciple of Swami Laxman joo, a Shaivite saint of Kashmir, India, for her blessings. She said, "While we have taken the path to understand the nature of the creator of this universe, you as scientists are in quest toward understanding the nature of the creation, both physical and biological, and hence there is a bonding between science and spiritualism."

My thanks are due to Prof. Mauro Giacca, former Director General, ICGEB, and Dr. Dinkar Salunke, Director, ICGEB, New Delhi Component, for offering me the Arturo Falaschi Emeritus Scientist position at ICGEB and providing me an office and lab space post retirement.

I am also thankful to the Government of India for their recognition and selecting me as Science and Engineering Research Board Distinguished Fellow and providing me personal and grant support to carry on with my research interests.

Thanks are due to the staff of Springer Nature, Ms Mamta Kapila, Raman Shukla, Vaishnavi Venkatesh and Metilda Nancy Marie Rayan. T for their support and understanding.

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About the Editor

Sudhir Sopory completed his Ph.D. degree from University of Delhi, and later worked at the Jawaharlal Nehru University, New Delhi. He got trained at the Max Planck Institute in Cologne, at the University of Munich in Germany, at the University of Texas, Austin, and at the United States Department of Agriculture, Beltsville, USA. He served as a Group Leader, Director, and later as Arturo Falaschi Emeritus Scientist at the International Centre of Genetic Engineering and Biotechnology. He was also the Vice Chancellor of Jawaharlal Nehru University, New Delhi.

He is an elected fellow of the major Indian science academies and The World Academy of Sciences (TWAS) and has received numerous honours, including the 1987 Shanti Swarup Bhatangar Prize, the highest Indian award in science and technology. The Government of India awarded him the fourth highest civilian honour of the Padma Shri, in 2007, for his contributions to science and technology.

He is currently a Science and Engineering Research Board, Government of India Distinguished Fellow at the International Centre for Genetic Engineering & Biotechnology, New Delhi, India.

Abbreviations

12-OPDA	12-oxo-10, 15-phytodienoic acid
2,4-D	2,4-dichlorophenoxyacetic acid
5HT	5 hydroxytryptamine
7TM	Seven transmembrane
ABA	Abscisic Acid
ABA2	*ABA DEFICIENT 2*
ABCB19	ATP-Binding Cassette B 19 protein
ABI	Abscisic acid insensitive
ABI4/5	*ABSCISIC ACID INSENSITIVE 4/5*
ABRE	ABA responsive promoter element
ACA	Auto-inhibited Ca^{2+}-ATPases
ACC	1-Aminocyclopropane-1-Carboxylic Acid
AChE	Acetylcholinesterase
ADH1	Alcohol dehydrogenase 1
AG	Arabinogalactan
AGO1	Argonaute
AGP	Arabinogalactan protein
AHK	Arabidopsis histidine kinase
AHK1	Arabidopsis histidine kinase 1
AHP	Arabidopsis histidine phosphotransfer protein
AMF	Arbuscular mycorrhizal fungi
AMPK	AMP-ACTIVATED PROTEIN KINASE
AMTs	Ammonium transporters
AOA	Aminooxyacetic acid
AP	Action Potentials
AP2	Apetella 2
AP2/ERF	APETALA 2/ERE binding factor
AP3	APETALA3
APX	Ascorbate Peroxidase
AqPs	Aquaporins
Ara	Arabinose
AREB/ABF	ABA responsive element (ABRE) binding factors
ADP-RF	ADP-ribosylation factor
ARF	Auxin response factor

ARFs	AUXIN RESPONSE FACTORs
ARR	Arabidopsis response regulator
ASA	Ascorbic Acid
ASMT	Acetylserotonin-*O*-methyltransferase
Asp	Aspartate
ATP	Adenosine triphosphate
AUX1	Auxin transporter 1
BABA	β-amino butyric acid
BetP	Glycine betaine transporter
bHLH	Basic Helix Loop Helix
BIC	Blue-Light Inhibitor of Cryptochrome
BLUS1	Blue Light Signalling 1
BR	Brassinosteroid
BRI1	BRASSINOSTEROID-INSENSITIVE 1
bZIP	Basic leucine zipper
BZR1	BRASSINAZOLE RESISTANT1
CA	Carbonic anhydrase
Ca^{2+}	Calcium Ions
CaCA	Ca^{2+}/cation antiporters
cADPR	cyclic ADP ribose
CaM	Calmodulin
CaMK	CaM-activated kinases
cAMP	Cyclic adenosine monophosphate
CAMTA	CaM-binding transcription activator
CAT	Catalase
CBF1	C-repeat Binding Factor 1
CBL	Calcineurin B-like
CC	Companion Cells
CCA	Circadian cock-associated
CCaMK	Ca^{2+} and CaM activated kinases
CCT	Cryptochrome Carboxyl Terminus
CDF	Cycling DOF Factor
CDPKs	Ca^{2+} dependent protein kinases
CesA	Cellulose synthase
CEZ	Central elongation zone
cGMP	Cyclic Guanosine monophosphate
CHASE	Cyclases/Histidine kinases associated sensory extracellular
ChAT	Choline acetyltransferase
CHK	CHASE domain containing histidine kinase
CIB1	Cryptochrome-Interacting Basic-Helix-Loop-Helix Protein
Cis-OPDA	Cis-(+)-12-Oxo-Phytodienoic Acid
CK	Cytokinin
CKI	Cytokinin insensitive
Cl^-	Chloride Ions
CLC	Chloride channel family

CMF	Cellulose microfibril
CML	CAM-Like
CNGC	Cyclic nucleotide gated channel
Cnr1	*cytokinin resistant 1*
CO	CONSTANS
CoI1	Coronatine Insensitive 1
COP	Constitutive Photomorphogenic
COP1	Constitutive Photomorphogenic 1
CPK	Calcium-dependent protein kinase
CRAC	Ca^{2+} release activated Ca^{2+}
CRC	Central Columella Root Cap
CRF	Cytokinin response factor
CRK	CDPK-related protein kinases
CrRLK1	*Catharanthus roseus* Receptor-Like Kinase 1
Cry	Cryptochrome
CSC	Cellulose-synthesizing complex or cellulose synthase complex
CTR	Constitutive response
CTR1	CONSTITUTIVE TRIPLE RESPONSE 1
CWD	Cell wall damage
CWDEs	Cell wall-degrading enzymes
CWI	Cell wall integral/integrity
DACC	Depolarization activated Ca^{2+} permeable channels
DAMP	Damage-associated molecular pattern
DBH	Dopamine-β-hydroxylase
DCL1	Dicer Like 1
DCMU	3-(3′,4′-dichlorophenyl)-1,1′-dimethyl urea
DD	Dopamine decarboxylase
DEK1	Defective Kernel 1
DET	De-Etiolated
DEZ	Distal elongation zone
DHA	Dehydroascorbate
DHAR	Dehydroascorbate Reductase
DNA	Deoxyribonucleic acid
DRMs	Detergent-resistant membranes
DTI	DAMP-triggered immunity
E2F	E2 FACTOR
eATP	Extracellular ATP
ECA	ER-type Ca^{2+}-ATPases
ECM	Extracellular matrix
ECM	Extracellular matrix
EPR	Electron paramagnetic resonance
ED	Ectodomain
EDRF	Endothelium-derived relaxing factor
EGF	Epidermal growth factor

EGTA	Ethylene glycol-bis (*b*-amino ethylether)-*N*, *N*, *N*′, *N*′-tetra acetic acid
Ehd1	Early Heading Date 1
EIL	Ethylene insensitive 3-like
EIN	Ethylene insensitive
EIN3/4	ETHYLENE-INSENSITIVE 3/4
EMF	Earth's Magnetic Field
ER	Endoplasmic reticulum
ERF	Ethylene response factor
ERMK	Elicitor responsive MAPK
ERS	Ethylene response sensor
ET	Ethylene
Eth	Ethylene
ETR	Ethylene response
ETR1/2	ETHYLENE RESPONSE factor 1/2
EXT	Extensin
EZ	Elongation zone
FAD	Flavin Adenine Di-Nucleotide
FER	FERONIA
FHL	FHY1 Like
FHY	Far Red Elongated Hypocotyl
FKF1	Flavin-Binding Kelch Repeat F-Box 1
FLC	Flowering locus c
FMN	Flavin Mononucleotide
FPI	Floral Pathway Integrator
FLT	Flowering Locus T
FT	Flowering Time
Fuc	Fucose
FUS	FUSCA
GA	Gibberellic acid
GABA	Gamma-Aminobutyric Acid
GAF	c**G**MP-specific phosphodiesterases, **A**denylyl cyclases, and **F**hlA domain
Gal	Galactose
GalA	Galacturonic acid
GAP	GTPase activity accelerating protein
GCN2	General amino acid control non-derepressible 2
GDI	Guanine nucleotide dissociation inhibitor
GDP	Guanosine diphosphate
GEF	Guanine nucleotide exchange factor
Ghd7	Grain Number Plant Height and Heading Date 7
GI	GIGANTEA
GID1	GIBBERELLIN INSENSITIVE DWARF1
gin2	*glucose insensitive 2*
GlcA	Glucuronic acid

GLRs	Glutamate-like receptors
GPCR	G-protein coupled receptor
G-proteins	Guanine nucleotide-binding proteins
GPX	Glutathione peroxidase
GRP	Glycine-rich protein
GS	Gravistimulation
GSA	Gravity set point angle
GSG	Glutathione
GSNOR	S-nitroglutathione reductase
GSSH	Oxidized glutathione dimer
GTL1–SDD1	GT-2 LIKE 1 -STOMATAL DENSITY AND DISTRIBUTION1
GTP	Guanine triphosphate
GUN	Genome uncoupled
H_2O_2	Hydrogen peroxide
H_2S	Hydrogen Sulfide
HACC	Hyperpolarization- activated Ca^{2+} permeable channels
HAMPs	Herbivore Associated Molecular Patterns
HATS	High-affinity transport systems
Hd3a	Heading Date 3a
HFR1	Long Hypocotyl in Far-Red 1
HG	Homogalacturonan
HHK	Hybrid histidine kinase
HIR	High Irradiance Response
His	Histidine
HK	Histidine kinase
HKRD	Histidine Kinase-Related Domain
HKT	H^+/K^+ transporter
HLS1	HOOKLESS 1
HMA1	Heavy metal ATPase 1
HOG	High-osmolarity glycerol response
HPT	Histidine phosphotransfer protein
HR	Hypersensitive Response
HRGP	Hydroxyproline-rich glycoprotein
HSP	Heat shock protein
HXK1	HEXOKINASE 1
HY	Long Hypocotyl
HY5	Long Hypocotyl 5
HYH	HY5-Homolog
IAA	Indole acetic acid/auxin
IDP	Inherently Disordered Hydrophilic Protein
Ile	Isoluceine
InsP3	Inositol 1,4,5-trisphosphate
IP_3	Inositol-1,4,5-triphosphate
IP_6	Inositol hexakis phosphate
JA	Jasmonic Acid

JAZ	Jasmonate Zim-Domain
K^+	Potassium Ions
LAF1	Long After Far-Red Light 1
LATS	Low-affinity transport systems
LAX3	Aux1-Like Protein 3
L-DOPA	Dihydroxyphenylalanine
LFR	Low Fluence Response
LFY	Leafy
LHY	Late elongated hypocotyl
LKP2	Lov Kelch Protein 2
LOV	Light, Oxygen or Voltage Sensing Domain
LPR1	Low-phosphate root 1
LRC	Lateral Root Cap
LRR	Leucine-rich repeat
LTP	Lipid Transfer Proteins
MADS	Minichromosome Maintenance1, Agamous, Deficiens and Serum Response Factor
MAMP	Microbe-associated molecular pattern
MAP	Mitogen-activated protein
MAPK	Mitogen-activated protein kinase
MAPKK	Mitogen activated protein kinase kinase
MAPKKK	Mitogen activated protein kinase kinase kinase
MCA	Mid1-Complementing Activity
MCA1/MCA2	MID1-complementing activity 1/ MID1-complementing activity 2
MCUC	Mitochondrial Ca^{2+} uniporter complexes
MDHA	Monodehydroascorbate
MDHAR	Monodehydroascorbate Reductase
MEcPP	Methylerythritol cyclodiphosphate
MED	Mediator
meJA	Methyl jasmonate
Mg^+	Magnesium
MH	Monophenol hydroxylase
MID1	Mating pheromone-Induced Death 1
MIPs	Major intrinsic proteins
miRNA	Micro RNA
MKK	MAPK kinase
mLST8	mammalian LETHAL WITH SEC13 PROTEIN 8
MScL	Large conductance mechanosensitive ion channel
MscS	Mechanosensitive channels of small conductance
MSL	MscS-Like
MSL1/MSL3	MScS-like 1/MScS-like 3
MYB	Myeblastosis
Na^+	Sodium ions
NAADP	Nicotinic acid adenine dinucleotide phosphate

NADP	Nicotinamide Adenine Dinucleotide Phosphate
NADPH	Nicotinamide Adenine Dinucleotide Phosphate Hydrogen
NAE	*N*-Arachidonylethanolamine
NAGK	*N*-acetyl-L-glutamate kinase
NAMPs	Nematode Associated Molecular Patterns
NAS	*N*-acetylserotonin
NB	Nuclear Bodies
NBS-LRR	Nucleotide-binding site Leucine Rich Repeat
NGR	Negative gravitropic response of roots
NHX	Na^+/H^+ exchanger
NIR	Nitrite reductase
NLP7	Nodule inception-like protein 7
NO	Nitric oxide
NPF	Nitrate transporter 1/ peptide transporter family
NPH3	Non-Phototropic Hypocotyl 3
NR	Nitrate reductase
NRT2.1	Nitrate Transporter 2.1
NUE	Nitrogen use efficiency
NutUE	Nutrient use efficiency
OG	Oligogalacturonide
OGA	Oligogalacturonide
OmpR	Outer membrane protein R
OPDA	12-oxo-phytodienoic acid
OpuA	Osmoregulatory ATP-binding cassette transporter
OSCA	Reduced hyperosmolality-induced Ca^{2+} increase
PAE	Pectin acetylesterase
PAFT	Plant Acoustic Frequency Technology
PAMP	Pathogen-associated molecular pattern
PAMPs/MAMPs	Pathogen/Microbe Associated Molecular Patterns
PAP	3′-Phosphoadenosine 5′-phosphate
PAR	Photosynthetically Active Radiation
PAS	Per (period circadian protein)-Arnt (aryl hydrocarbon receptor nuclear translocator protein)-Sim (single-minded protein)
PCD	Programmed Cell Death
PCIB	p-chlorophenoxyacetic acid
PDR2	Phosphate deficiency response 2
PERKs	Proline-rich extensin-like receptor kinases
Pfr	Phytochrome-far red absorbing form
PGs	Polygalacturonases
PhANG	Photosynthesis Associated Nuclear Genes
PHF1	Phosphate transporter traffic facilitator 1
Phot	Phototropin
PHR	Photolyase Homology Region
Phy	Phytochrome
PHY	Phytochrome

PhyB	Phytochrome B
PI	PISTILLATA
PIF	Phytochrome Interacting Factor
PIN	PIN-formed
PKS4	Phytochrome Kinase Substrate 4
PLC	Phospholipase C
PLD	Phospholipase D
PLP	PAS/LOV protein
PM	Plasma membrane
PM	plasma membrane
PME	Pectin methylesterase
PNMT	Phenylethanolamine-*N*-methyltransferase
POD	Peroxidase
PR	Pathogenesis Related
Pr	Phytochrome-red light absorbing form
ProP	Proline/betaine transporter
PRR	Pattern recognition receptor
PsRR	Pseudo response regulator
PRSL1	Protein Phosphatase1 regulatory subunit2-like protein1.
PRX	Peroxiredoxin
PS	Photosystem
PSI	Phosphate starvation induced
PSRs	Phosphate stress responses
PTI	Pathogen Triggered Immunity
PTM	Post-translational modifications
PΦB	Phytochromobilin Chromophore
QTL	Quantitative trait loci
RALF	Rapid alkalization factor
RAPTOR	REGULATORY-ASSOCIATED PROTEIN OF mTOR
RBCS	Ribulose-1,5-bisphosphate carboxylase
RBOH	Respiratory burst oxidase homologue
RD	Receiver domain
RGA	Repressor of gibberellic acid
RG-I	Rhamnogalacturonan I
RGS	Regulator of G-protein signaling
Rha	Rhamnose
RHP1	RGS1-HXK1 INTERACTING PROTEIN 1
RICTOR	RAPAMYCIN-INSENSITIVE COMPANION OF MTOR
RLCK	Receptor-like cytoplasmic kinase
RLK	Receptor like kinase
RLP	Receptor-like protein
RNA	Ribonucleic acid
RNS	Reactive nitrogen species
ROP	Rho of plants
ROP2	Rho-related protein 2

ROS	Reactive Oxygen Species
RR	Response regulator
RSA	Root system architecture
RSS1	*REGULATED BY SUGAR AND SHADE1*
RUP	Repressor of UV-B Photomorphogenesis
S1P	Spingosine-1-phosphate c
S6K1	RIBOSOMAL PROTEIN S6 KINASE 1
SA	Salicylic acid
SAG	Senescence Associated Genes
SAR	Systemic Acquired Resistance
SAvR	Shade Avoidance Response
SAUR	Small auxin up RNA
SCF	SKP1/CULLIN1/F-BOX
SE	Sieve Elements
SEP	SEPALLATA
Ser	Serine
Sho1	High osmolarity signaling protein1
SHY2	*SHORT HYPOCOTYL 2*
SIPK	Salicylic acid induced protein kinase
siRNA	Small Interfering RNA
Sln1	Synthetic lethal of N-end rule 1
SLs	Strigolactones
SNAT	Serotonin-*N*-acetyltransferase
SNF1	SUCROSE NON-FERMENTING 1
SNO	*S*-nitrothiol
SnRK1	SNF1-RELATED PROTEIN KINASE 1
SOC1	Suppressor of Overexpression of Constans
SOD	Superoxide Dismutase
SOS	Salt-overly Sensitive
SP	Systemic Potentials
SPA	Suppressor of PHYA
SPL	SQUAMOSA promoter binding protein like
STIM	stromal interaction molecules
SV	slow vacuolar type
T-5-H	Tryptophan-5-hydrolyase
T6P	trehalose-6-phosphate
tasiR	Trans acting siRNA
TCH	Touch-inducible
TCL	Thin cell layer
TCS	Two-component system
TD	Transmitter domain
TDC	Tryptophan decarboxylase
TF	Transcription factor
TH	Tyrosine hydroxylase
THE1	THESEUS 1

Thr	Threonine
TIBA	2,3,5-triiodobenzoic acid
TLR	Toll-like Receptor
TML	Too Much Love, a Kelch-Repeat F-Box Protein
TOC	Translocon on the outer chloroplast membrane
TOR	TARGET OF RAPAMYCIN
TPC1	Two-pore channel1
TPK	Two-pore K^+ channel
TRPV4	Transient receptor potential cation channel subfamily V member 4
TRX	Thioredoxin
Tyr	Tyrosine
uORF	Upstream Open Reading Frame
UPS	Ubiquitin Proteosome System
UVR8	UV-B Resistance 8 *aka* Ultraviolet-B Receptor
VDAC	Voltage-gated anion channel
VICCs	Voltage-Independent Ca^{2+} Channels
VLFR	Very Low Fluence Response
VM	Vacuolar membrane
VOC	Volatile Organic Compound
VP	Variation Potentials
WAK	Wall-associated kinase
WAKLs	WAK-like kinases
WGD	Whole genome duplication
WIPK	Wound induced protein kinase
XG	Xyloglucan
XTH	Xyloglucan endotransglucosylase/hydrolase
Ypd1	Tyrosine phosphatase dependent 1
YUCCA	Flavin Monooxygenase-Like Enzyme
ZTL	ZEITLUPE
Ψ_p	Hydrostatic potential
Ψw	Water potential
Ψ_Π	Osmotic potential
Ψ_g	Gravitational potential