S. Dutta Gupta *Editor*

Light Emitting Diodes for Agriculture

Smart Lighting

Springer

Light Emitting Diodes for Agriculture

S. Dutta Gupta
Editor

Light Emitting Diodes for Agriculture

Smart Lighting

Springer

Editor
S. Dutta Gupta
Department of Agricultural and Food Engineering
Indian Institute of Technology Kharagpur
Kharagpur
India

ISBN 978-981-10-5806-6 ISBN 978-981-10-5807-3 (eBook)
DOI 10.1007/978-981-10-5807-3

Library of Congress Control Number: 2017946641

© Springer Nature Singapore Pte Ltd. 2017
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Dedicated to the Memory of
My Beloved Wife 'Rina'

Let the light shine!

Foreword

We are at the beginning of a technological revolution that will have immense long-term impact on all of our lives. The majority of all of the lighting in the world is transitioning from conventional lighting technologies: incandescent, fluorescent, metal-halide, and low- and high-pressure sodium to LED lighting. In the USA., LED lighting technology is projected to reduce the total energy budget, which includes all primary energy consumption, by 5% by 2035. This is a massive energy saving that equates to about $50B per year in energy savings in 2035, not to mention all of the benefits of CO_2 reduction associated with this savings.

While the initial driver for this shift was improved energy efficiency and resulting energy savings, the value proposition for LED lighting technology has moved well beyond this initial and important benefit. Not only is LED technology more efficient than conventional sources, it is longer lived and can provide improved lighting performance across the board. Due to their improved efficiency, LEDs run cooler reducing thermal load on heating, ventilation, and air-conditioning "HVAC" systems. They have smaller optical source size, enabling improved control of optical distribution. They can last 50,000 h or more. They can be turned on and off instantaneously, and they are fundamentally dimmable. Finally, the spectral power density of the emitted light can be finely engineered and even made to be actively tunable. At this time, early 2017, most products do not fully engage all of these advancements due to cost, form factor, or engineering trade-offs, but consumers are learning to expect more and developers of LED technology are rapidly improving the lighting value with fewer compromises out of their lighting products.

The same technology advancements that are improving general illumination are also being applied to other lighting applications, in particular the use of LED lighting for controlled environment agriculture. LED lighting technology enables a more highly controlled growth environment that can improve productivity and control of the horticultural product. LED lighting may even enable new crops to be effectively produced in controlled environments. New levels of control over spectral power distribution, optical intensity distribution, form factor, and active color tuning can be used to tailor the light to specific crops, improve productivity, and control aspects of the plant growth such as height, bushiness, and color or nutritional content. As these new levels of control are being explored for various plant growth and development applications, increasing the value of the light, the cost of LED lighting products continues to decrease.

Not only can the features of LED lighting be used to improve production but the new control can also be used as a highly configurable research tool to refine our knowledge of plant physiological responses to light at a rapid pace. This book serves to connect the latest research in plant and biological responses to light with developments in LED lighting technology. There is a vast range of plant physiological responses to light for a vast range of plant species and cultivars. And now we have a vast range of control over the light they experience in terms of color, intensity, optical distribution, and changes in these factors over time. Understanding and harnessing the impacts of LED lighting on agriculture requires a long-term research effort. This book provides a range of research results in terms of lighting attributes, plant and cellular physiological responses, and even economics of lighting for controlled environment agriculture. Configurable LED lighting is now relatively inexpensive, allowing for researchers across the globe to conduct meaningful experiments and add to the body of knowledge for this important topic. Academic, commercial, and neophyte researchers can use the research described in this book as a starting point for their own research efforts.

This book contains fourteen chapters, contributed by pioneers who are leading the emergence of LED technology for controlled environment agriculture across the globe. The chapters follow a sequence from fundamental features of LED, their use as supplemental lighting system, economics and various applications in controlled environment agriculture and their role in regulating plant morphogenesis both in vivo and in vitro. I am confident that the present book will motivate plant scientist and biotechnologists to enter into this fascinating field of application of semiconductor lighting technology for the improvement of plant growth and development.

The use of LED lighting for agricultural/horticultural applications has profound implications for our world. LED lighting is a key and enabling component of controlled environment agriculture, which allows for growth of crops in new regions of the world at any time of year. This changes how crops and growth locations are chosen with respect to targeted markets. Energy, water, chemical, and nutrient inputs for plant growth are also dramatically changed with controlled environment agriculture. The long-term impacts on our global food supply are likely to be more localized production, increased self sufficiency, more nutritious produce available year-round, and increased opportunity for consistent small-scale food production, just to name a few of the likely impacts. While the full global impact of LED-enabled controlled environment agriculture with the knowledge of role of light in plant morphogenesis is difficult to anticipate, LED-regulated plant growth and development are certainly poised to play an expanded role in how the world gets its food and understanding the concepts put forth in this book will be critical to making this vision a reality.

P. Morgan Pattison, Ph.D.
President and Founder of
Solid State Lighting Services, Inc.
Senior Technical Advisor
United States Department of Energy
Solid State Lighting R&D Program
Washington, USA

Preface

Light plays a pivotal role in regulating plant growth and development. Both quality and intensity of light as well as the photoperiod are very critical for plant morphogenesis. The significance of plant photoreceptors as key regulatory proteins that govern metabolic events and developmental changes within plants has been well documented. Complex, multiple photoreceptor systems respond to light and thereby regulate plant morphogenetic changes, functioning of the photosynthetic apparatus, and the trend of metabolic reactions. Moreover, photooxidative changes evoked by lighting condition may lead to the altered action of antioxidant defense system. Thus in combination with other agro-technical means, light, creating the mild photo-stress, might be an effective tool for phytochemical rich plant cultivation.

Crop failure due to unpredictable climate change is a matter of global concern. Threats such as pest attacks and diseases further aggravate the uncertainty of crop yields. Geo-climatic limitations of traditional agriculture and its dependence on environmentally hazardous fertilizers and pesticides have impelled the advancements in controlled environment farming techniques. The concept of controlled environment agriculture in greenhouses and closed plant production system has emerged as a reliable and sustainable alternative means of crop production. These “plant factories” for vertical farming are now becoming an indispensable part of the global food security system. However, the feasibility and sustainability of such systems are largely dependent on the power requirements. The large power requirements mainly from the electric lamps that provide the actinic light which drives the light reactions of photosynthesis, accounting for 40% of the recurring cost of plant factories, are the major bottlenecks to make controlled environment agriculture profitable.

The light source generally used for controlled environment agriculture is fluorescent light, metal-halide, high-pressure sodium, and incandescent lamps. Among them, fluorescent lamp has been the most popular. However, these lighting systems have a wide range of wavelengths from 350 to 750 nm and are of low quality for promoting plant growth and development. They also emit light with low photosynthetic photon flux and had limited lifetime of operation which restricts their utilization in plant lighting systems when the goal is to sustain high crop productivity.

The steady development of the light-emitting diode (LED) technology with the emergence of new types of semiconductor materials has made it possible to apply it in an increasing number of new areas including plant growth and development. As an alternative to conventional lighting system, LED has been demonstrated to be an artificial smart lighting source for controlled environment agriculture and in vitro studies of plant morphogenesis. Various morphological, anatomical, and physiological attributes of plants grown both in vivo and in vitro have found to be regulated by spectral properties of LED. Apart from its regulatory role in plant growth and development, LED affects the amplification of functional components which contribute toward the selective control of antioxidative attributes. Since the LED emits over specific spectral regions, they can be used to regulate the levels of photosynthetically active and photomorphogenic radiation necessary for plant growth and development. This feature allows implementation of LED with specific spectral ranges that are involved in plant responses and also ensures the independent control of each spectral range and precise manipulation of spectral quality and light intensity. The flexibility of matching wavelengths of LED to plant photoreceptors may provide optimal production influencing plant morphology and metabolism. These solid-state light sources are therefore ideal for use in plant lighting designs for controlled environment agriculture as well as for studies on photomorphogenesis.

The present book aims to present a comprehensive treatise on the advancements made in the use of LEDs for sustainable crop production and to describe research achievements on photomorphogenesis. This book introduces readers to the fundamentals and design features of LEDs applicable for plant growth and development and illustrates their various advantages over the traditional lighting systems with cost analysis. It contains 14 chapters, and organizes the information in order to present a wide spectrum of applications of LEDs covering a diverse domain of plant sciences relevant to controlled environment agriculture and in vitro plant morphogenesis. The scope of this book has been expanded by including chapters that deal with the role of LEDs in regulating cellular redox balance, nutritional quality, and gene expression. The chapters are written by a team of international experts who are pioneers, and have made significant achievements in this emerging interdisciplinary enterprise. I am indebted to the chapter contributors for sharing their research outcomes and kind support. I am grateful to Dr. P. Morgan Pattison for sparing his valuable time to write the “Foreword.” Thanks are also due to Mr. Arjun Karmakar and Ms. Nirlipta Saha for their help in checking the cited references.

It is the invisible inspiration and encouragement of my beloved wife Rina (Dr. Rina Dutta Gupta) that raise me up to take the task of compilation of this book on LED lighting and their impacts on plant growth and development. She holds the light from her heavenly abode throughout the path of my endeavor and no words can describe and acknowledge such bestowed strength which motivates me.

Kharagpur, India S. Dutta Gupta
February 2017

Contents

About the Editor

Dr. S. Dutta Gupta is currently a Professor in the Department of Agricultural and Food Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India. He has been engaged in teaching and research on plant biotechnology for more than 30 years. He is a pioneer in the application of artificial intelligence and imaging techniques in plant tissue culture system and brings engineering–plant tissue culture link to a new dimension of understanding. He has also made a significant contribution to light-emitting diode (LED)-assisted modifications of oxidative status during shoot organogenesis. Dr. Dutta Gupta has received fellowships from various agencies and governments such as the United States Department of Agriculture (USDA), Lockheed Martin, the Ministry of Human Resource Development (MHRD), the Indian National Science Academy (INSA), the Council of Scientific and Industrial Research (CSIR), the Department of Science and Technology (DST), the Czech Academy of Sciences, and the Japan Society for the Promotion of Science (JSPS). He has published more than 100 scientific articles and edited four books.

Chapter 1
Artificial Lighting System for Plant Growth and Development: Chronological Advancement, Working Principles, and Comparative Assessment

S. Dutta Gupta and A. Agarwal

1.1 Introduction

Solar radiation is the primary source of energy that sustains life on earth. The spectral distribution of solar radiation has a broad waveband ranging from 300 to 1000 nm. However, only 50% of the radiant energy is available to plants as photosynthetically active radiation (PAR) and comprises the wavelength region from 400 to 700 nm (Boyle 2004). Specialized photoreceptors present in the plant leaves capture the photons and convert the sun's radiant energy to chemical energy following the process of photosynthesis. The process utilizes light absorbed by chlorophyll *a* and *b*, the most important photosynthetic pigments, at 662 and 642 nm, respectively. Plants have also developed intricate mechanisms for transducing the different wavebands of the incoming solar radiation into specific chemical signals for regulating various complex growth and developmental processes. Other than high-energy-dependent process of photosynthesis, photomorphogenesis, photoperiodism, and phototropism are also significantly influenced by the ambient light conditions. Photomorphogenesis is defined as light-mediated plant development that also includes differentiation of cells, tissues, and organs and depends on far-red radiation in the range of 730–735 nm, whereas photoperiodism refers to the ability of plants to sense and respond to the changes in the photoperiod: the relative lengths of day and night. The growth movement of the plants toward the direction of its light source is termed as phototropism. Light in the wavelengths range of 400–500 nm triggers the phototropic processes.

Unpredictable changes in the natural lighting conditions, insufficient daylight during the winter season, and climate change phenomenon lead to suboptimal yields and crop failures in many parts of the world. In order to mitigate this low

---

S. Dutta Gupta (✉) · A. Agarwal
Agricultural and Food Engineering Department, Indian Institute
of Technology Kharagpur, Kharagpur 721302, India
e-mail: sdg@agfe.iitkgp.ernet.in

S. Dutta Gupta (ed.), *Light Emitting Diodes for Agriculture*,
DOI 10.1007/978-981-10-5807-3_1

crop productivity, the concept of protected cultivation in greenhouses and controlled environment crop production facilities with artificial lighting came into existence (Mpelkas 1980). Artificial light sources are used to augment insufficient sunlight in greenhouse-based open production system, whereas crop and/or transplant production in closed production system relies upon electrical lighting as the sole light source. Plant tissue cultures maintained under in vitro conditions depend entirely upon artificial light sources for illumination.

The earliest reports of plant growth under artificial lighting were published in the 1860s by H. Mangon, E. Prilleux, and others. However, commercial application of artificial lighting for crop production took place only after the development of more robust and long-lasting electrical lamps in the early twentieth century (Pinho and Halonen 2014). In the present scenario, electrical lamps have become an indispensable tool for controlled environment agriculture as a steady and reliable source of plant lighting. Technological advancement in artificial lighting over more than a century has made it possible to attain the present state of the art in electric lamp designs.

The most preliminary electrical lamps were designed in the first half of the nineteenth century. The model for an “electric arc” lamp was demonstrated by Sir Humphry Davy in 1809, whereas the first prototype for an “incandescent” lamp was revealed by Warren de la Rue in 1840. The era of artificial electric lighting actually started with the development of incandescent lamp designed by Thomas Edison in 1879. The proposed models were too costly for commercial application and had very short life spans. Various “carbon-filament”-based models were designed for the incandescent lamp in the mid- and late nineteenth century. However, it was only in the first part of the twentieth century that tungsten-based incandescent lamps were developed. Gas discharge lamps, the next state of electro-optical advancement, were first fabricated by Heinrich Geissler in 1857 by using various noble gases in an electric arc tube. The fluorescent lamp is the most widely used gas discharge lamp and utilized extensively in plant growth applications due to its reasonable energy efficiency and life span. Afterward, the introduction of metals such as mercury and sodium into the discharge tube improved the illumination as the electrical current was channelized through the vaporized metal. The first widely accepted design for the mercury vapor lamp was produced by P.C. Hewitt in 1901. This design was further improved by various others, and in 1936, the first modern high-pressure gas discharge lamp was launched by Philips. In the following decade gas discharge lamps having higher luminous efficacy and better spectral output such as metal-halide lamps and high-pressure sodium lamps were developed. High-pressure discharge lamps have been the preferred light source for crop production in controlled environment agriculture. The high PAR emission with relatively high percentage of blue radiation, long life span, and the electrical efficiency in the range of 25–40% make these lamps an option to replace daylight totally or partially supplementing it for year-round cultivation (Simpson 2003). However, conventional light sources suffer from the poor ability of efficient use of energy. Further, the spectral quality specific to photosynthesis as well as photomorphogenesis cannot be controlled during lighting treatment. Such limitations of conventional light sources accelerated the emergence of LEDs as potentially viable and promising artificial light source in controlled environment agriculture. The practical implementation of LEDs originated from the experiment of Henry Josef Round, a radio engineer in Marconi Labs, who observed the emission of light from a silicon carbide crystal when a current flowed through the material. This was the very first demonstration of a solid-state lighting, and the light produced is based on an electroluminescence effect (Round 1907). In spite of this breakthrough, technological advancement of LEDs was relatively slow until the 1960s (Schubert 2003). Since the invention of the first commercial LED in the late 1960s, there has been a gradual improvement in LED design with the advancement of semiconductor technology. The new-generation LEDs have also become a promising light source for plant growth research and cultivation, besides its popular applications as indicators and optoelectronic devices.

Impact of electrical lighting on plant growth and development was studied by many scientists using contemporary incandescent lamps and electric arc lamps. As reported by Siemens in 1880, plants illuminated by carbon arc lamps in addition to sunlight displayed improved growth when compared to the naturally growing plants. Studies on various food crops under tungsten-based incandescent lamps suggested that it could be possible to grow crops independent of sunlight and could be made to reach maturity and set seed even during the winters (Harvey 1922). In 1926, Pfeiffer reported that the duration of artificial lighting had a significant impact on the phyto-constituents of various plants. Over the years, various electrical lamps such as incandescent lamps (ILs), fluorescent lamps (FLs), high-pressure mercury vapor lamps (HPMLs), high-pressure sodium vapor lamps (HPSLs), and metal-halide lamps (MHLs) were employed for experimental plant growth applications and commercial plant cultivation. However, the potential of light-emitting diodes (LEDs) as a photosynthetic radiation source for plant growth was first explored in the early 1990s (Bula et al. 1991, 1992). The outcome of these studies unveiled some of the advantageous features of LEDs and clarified certain plant morphogenic responses related to the spectral quality of lighting source. A major breakthrough in the LED technology was attained with the development of first viable high-brightness blue LED by Shuji Nakamura in 1993 (Nakamura and Fasol 1997; Nakamura et al. 2000). This achievement paved the way for utilization of LEDs in plant growth and development.

The overall aim of this chapter is to present the reader a basic introduction to artificial lighting systems used in plant growth and development with their technological advancement over time, working principles and attributes with respect to spectral quality, luminous efficacy, power consumption, heat generation, and life span. Finally, a comparative assessment of the various performance parameters of the different light sources has been presented to highlight the advantageous features of LEDs and its potential as a photosynthetic radiation source for growing plants in controlled environment. With a basic understanding of the electrical and optical properties of the artificial lighting system, readers with plant science background will be well placed to comprehend the specific function and applications of LEDs discussed in the rest of the book.

1.2 History of Development and Working Principles of Conventional Lamps

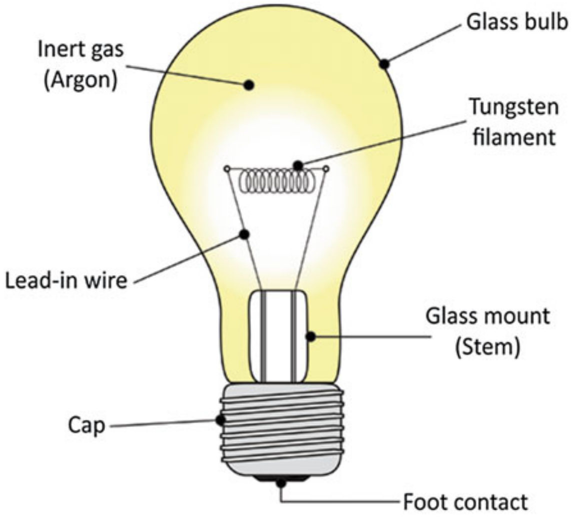
Conventional plant lighting sources include incandescent, fluorescent, high-pressure mercury, high-pressure sodium, and metal-halide lamps. Incandescent lamps emit light upon the heating up of a metal filament, the phenomenon being called incandescence. The fluorescent, high-pressure mercury, high-pressure sodium, and metal-halide lamps are gas discharge lamps (GDLs) since they emit light generated by an electrical discharge through an ionized gas. Emission from incandescent lamps consists of thermal radiations, whereas GDLs emit photons by the release of energy from thermionically excited electrons. Among the GDLs, the FLs are low-pressure lamps, whereas the HPMLs, HPSLs, and MHLs are termed as high-intensity discharge lamps (HIDLs) due to the high pressure of gases in the arc tube. This section outlines the technological advancement toward the present-day conventional lamps from the preliminary models and illustrates their working principles.

1.2.1 Incandescent Lamps (ILs)

Incandescence, the working principle behind ILs, is the phenomenon by which a solid starts emanating electromagnetic radiations in the visible range upon being heated (Kitsinelis 2011). The oldest design for the incandescent lamp proposed by Rue in 1840 consisted of a platinum coil enclosed in an evacuated glass tube. The design was not cost-effective due to the platinum coil. Experimental designs replacing the platinum with charcoal, carbonized paper, and carbonized bamboo filaments were proposed by others. The challenges faced by the inventors included the short life span of the filament and the blackening of the bulb caused by the burning of the filament. The lamp developed by Woodward and Evans in 1874 comprised of a glass bulb filled with nitrogen housing a carbon rod connected to two electrodes. In spite of this improvement in the design feature, it was not accepted for commercialization. In 1879, Edison purchased the patent for this design and using the model developed an incandescent bulb that not only performed better but was also more convenient to use in a cost-effective manner. He received the patent for this bulb in 1880 and commercialized it. However, it was only in 1904 that Hanaman and Just developed the first tungsten filament-based incandescent lamp which was further improved by General Electric (commonly known as GE) in the following years. Further refinements in the tungsten filament lamp involved the production of improved filament and the use of noble gases instead of evacuating the bulb.

Modern ILs are composed of an airtight glass bulb with a tungsten filament connected to lead-in wires (Fig. 1.1). The bulb is essentially made devoid of oxygen by evacuation or by filling up with an inert gas to prevent the burning up of the filament. The filament is made of a metal having high melting point and low

Fig. 1.1 Structure of an incandescent lamp



coefficient of thermal expansion. Tungsten, possessing both these properties, has practically been the only metal used for producing the filament for ILs since the early twentieth century. The two lead-in wires connected to either ends of the filament are connected to the external circuit. The lamp operates when the electrical current flows in from one lead wire, through the filament and out of the second lead wire. As the filament has higher resistivity than the lead-in wires, it impedes the flow of electrons. The inelastic collisions between the moving electrons and the electrons within the filament lead to the conversion of the kinetic energy of the moving electrons into atomic vibrational energy. This causes the filament to gradually heat up and start dissipating energy as electromagnetic radiations. As the temperature of the filament rises up to almost 2800 K, it emits radiations in the entire visible range, with the intensity of radiations increasing from 400 to 700 nm. A significant portion of the energy is also dissipated as far-red emission which can reach up to 60% of the total PAR.

Early trials with ILs exhibited their potential for usage in indoor cultivation during winters as they not only produced a broad-spectrum emission but also provided warmth to the plants. However, the operations were not deemed economically feasible owing to the low luminous output in exchange of the high electricity input. Heat losses and poor electrical efficiency outweighed the gain in plant growth and yield. The energy conversion efficiency for the various modern ILs ranged between 1 and 5%, with the luminous efficacy never exceeding 20 lm/W (lumens/watt). Availability of power-efficient and long-lasting GDLs gradually replaced the ILs as a light source for indoor cultivation. Moreover, high power consumption along with low luminous efficacy has led to the phasing out of ILs, banning their manufacture, import, and sales in many countries.

1.2.2 Gas Discharge Lamps (GDLs)

The carbon arc lamp demonstrated by Sir Humphry Davy in 1809 was the predecessor of all modern GDLs (Zissis and Kitsinelis 2009). The arc lamp worked on the principle of sustaining an electric arc or flow of electricity between two electrodes via an intervening gaseous medium. Davy's arc lamp involved the electrical breakdown of air or ionization of air molecules which maintained an electrical discharge between two carbon electrodes resulting in thermionic excitation of electrons leading to the emission of faint light. Lightning, a common natural phenomenon, is an example of an electric arc formed by the breakdown of molecules present in the air. In 1857, Heinrich Geissler demonstrated the world's first low-pressure mercury vapor discharge lamp. The mercury vapor discharge lamp produced a strong greenish-blue glow but had a short operating life. Peter Cooper Hewitt patented the mercury vapor lamp in 1901 after making certain improvements in Geissler's design. However, the application of this lamp was limited owing to the characteristic color of light it gave off. During that period, many scientists including Edison and Tesla tried to improve gas discharge lamps but success was limited. In 1906, a high-pressure mercury vapor lamp having a quartz arc tube was developed by Küch and Retschinsky. The next major step was the successful application of fluorescent coatings on the inside of the glass arc tube of mercury lamps by Compton in 1934. Application of halophosphate phosphor coatings resulted in the emission of white light from the low-pressure mercury vapor lamps. Philips launched the first high-pressure mercury vapor lamps in 1936, whereas General Electric became the first to commercially produce fluorescent lamps in 1938. Several experiments revealed that vaporized metals had a better emission spectrum at high pressures than at low pressures. However, glass arc tubes that could withstand such high pressures along with the high operating temperature without reacting with the vaporized metal were not available at that period. In 1955, R.L. Coble developed an aluminum oxide ceramic that could be used for making the arc tube for high-pressure sodium lamps. In 1962, metal-halide lamps were developed by Robert Reiling who introduced halides of metals in the high-pressure mercury lamp, resulting in a better emission spectrum than the mercury vapor ones. High-pressure sodium lamps emitting bright white light developed by Homonnay, Louden, and Schmidt were launched commercially in 1964.

1.2.2.1 Fluorescent Lamps (FLs)

As mentioned earlier, FLs are low-pressure mercury vapor discharge lamps that produce visible light due to the fluorescence of a phosphor coating. FLs may be divided into two classes on the basis of their shape and size—tubular and compact (Fig. 1.2). Although the luminous efficacies of the two designs differ significantly, the working principle for both types of FLs is essentially the same. Both of them consist of an airtight hollow glass tube filled with a mixture of mercury and argon

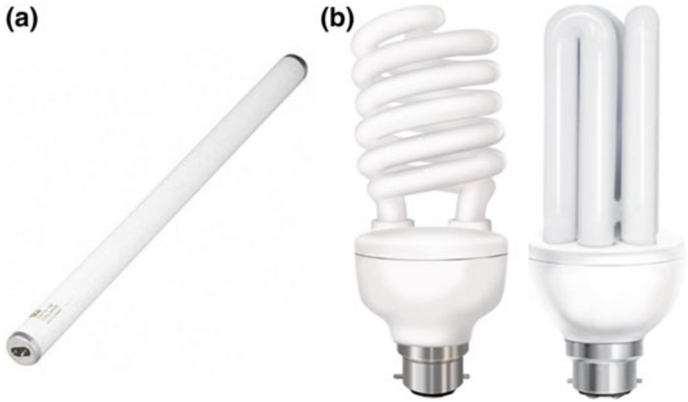


Fig. 1.2 Tubular (**a**) and compact (**b**) fluorescent lamps

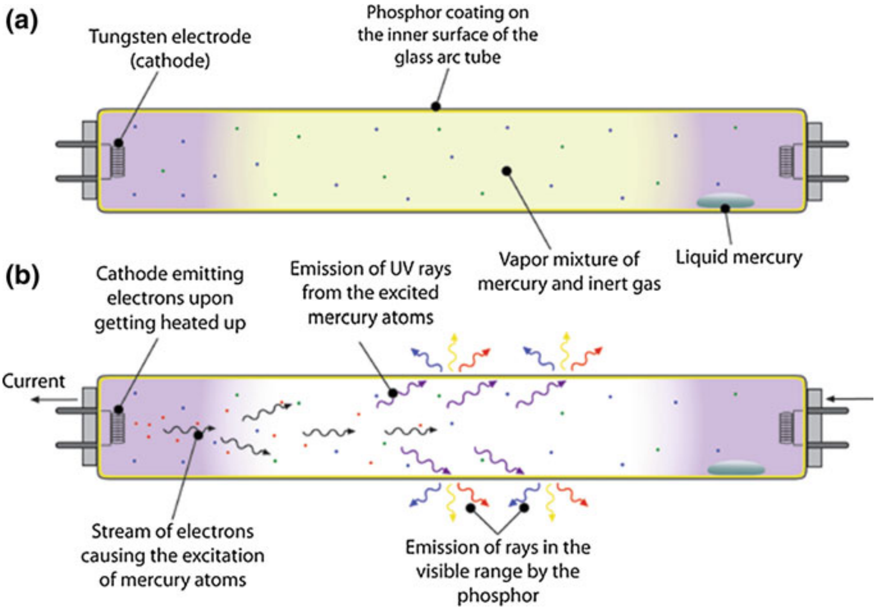


Fig. 1.3 Components (**a**) and functioning (**b**) of a fluorescent lamp

vapors in a low-pressure environment (Fig. 1.3a). The inert gas present in the arc tube promotes the ionization of the gaseous metal (mercury) atoms. The two ends of the tube have electrodes composed of tungsten filaments projecting into the vapor mixture. Upon the passage of electricity, the filament gets heated up and starts emitting electrons (Simpson 2003). Since FLs work on alternating current, the two electrodes alternately emit electrons every half cycle. The electrons get accelerated toward the opposite electrode through the mercury vapor mixture due to the applied voltage. The electrons collide with the valence electrons of the mercury atoms causing electron impact ionization which leads to the release of more free electrons into the vapor mixture, a condition also referred to as breakdown. At this stage, the vapor starts conducting electricity freely. The mobile electrons cause the excitation of the other electrons in the outer orbitals of the mercury atoms. The excited electrons fall back to the ground state and in the process emit radiations in the UV range (Fig. 1.3b). These high-energy UV photons are absorbed by the phosphor coating which fluoresces or starts emitting photons of lower energy, i.e., within the visible range. Since the emission spectrum of an FL entirely depends upon the phosphor coating, a wide variety of phosphors have been used for developing white and colored FLs.

Energy losses in an FL occur in the ballast which supplies a pulse of high voltage to initiate the discharge. However, a significantly higher amount of energy is lost during the conversion of UV rays into visible light where almost half the energy of each photon is lost as heat. Since they were first launched commercially, fluorescent lamps (FLs) have been modified significantly for improving the luminous efficacy and reducing the cost of production. However, the overall energy conversion efficiency of the FLs is still below 30% (Shur and Žukauskas 2005). FLs have been a popular source of plant lighting in small- and large-scale operations owing to the white light output that appositely mimics daylight. Approximately 90% of the photons emitted are in the PAR region. However, spectral output of FLs cannot be regulated and the surface of the lamp becomes considerably hot during operation.

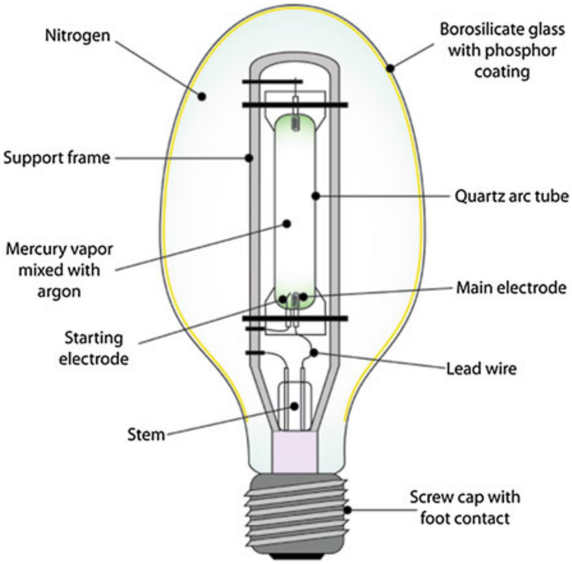
1.2.2.2 High-Intensity Discharge Lamps (HIDLs)

HIDLs, also known as high-pressure discharge lamps, operate at very high pressures and temperatures. Like FLs, HIDLs also work on the principle of electric discharge through a gas and require ballasts for creating a striking voltage and maintaining the arc. However, the high operating pressure and temperature of HIDLs plays an important role in improving the spectral output and increasing the luminous efficacy. This is due to the fact that vaporized metals conduct electricity better under high pressure leading to higher number of electron excitations and more thermionic emissions (Kitsinelis 2011). HIDLs may be broadly classified into three types depending upon the “fill-gas” or vapor used—mercury, sodium, and metal halide (Fig. 1.4). It is worthy to note that all HIDLs essentially contain mercury in the fill-gas along with the other vapors.

As in FLs, the HPMLs contain a mixture of mercury and argon vapors, but at almost 200,000 times the pressure in an FL. The vapors are maintained in a quartz arc tube to withstand the high pressure and operating temperature (Fig. 1.5). The arc tube is housed inside an outer envelope made of borosilicate glass filled with nitrogen. The ionization of mercury atoms is triggered by the emission of electrons from the tungsten electrodes. However, due to the high pressure, the frequency of

Fig. 1.4 High-pressure mercury lamp (**a**), high-pressure sodium lamp (**b**), and metal-halide lamp (**c**)

Fig. 1.5 Design features of a high-pressure mercury vapor lamp



electron impacts on the mercury atoms becomes very high. This leads to the generation of a huge amount of heat. As a result, the mercury electrons get ionized to higher excitation states, leading to the emission of radiations at certain wavelengths in the visible range along with the UV radiations. A phosphor coating provided on the outer envelope converts the UV radiations into different visible wavelengths, resulting in white light (Kitsinelis 2011).

Despite the high-pressure discharge conditions, HPMLs have a luminous efficacy of around 60 lm/W. High lumen output has made the HPMLs suitable for various applications such as overhead lighting in factories and warehouses as well as street lighting.

The HPSLs have greater coverage over the visible spectrum than the mercury vapor lamps due to the presence of sodium vapors along with mercury in the arc tube. Further, the tube is pressurized with xenon instead of argon. The vapors are maintained within a ceramic or polycrystalline alumina tube which can withstand the corrosive nature of sodium vapors at high temperature and pressure (Kitsinelis 2011). The excitation of mercury and sodium atoms occurs by the bombardment of electrons from the tungsten electrodes. The electron impact ionization coupled with thermal ionization results in electrons jumping to various higher energy states, while falling back to the ground state, the electrons emit electromagnetic radiations covering a wide range in the visible spectrum. The components of HPSLs are depicted in Fig. 1.6.

Higher luminous efficacy (80–125 lm/W) and broad emission spectrum of HPSLs have made them a popular source of electrical lighting in public spaces and industrial buildings. A high emission peak in the 560–610 nm range renders a distinct yellow coloration to the light produced which limits its applications.

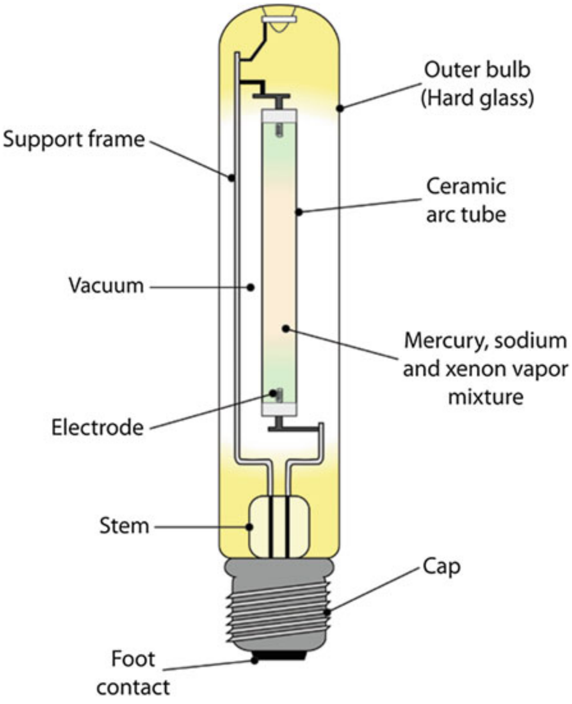
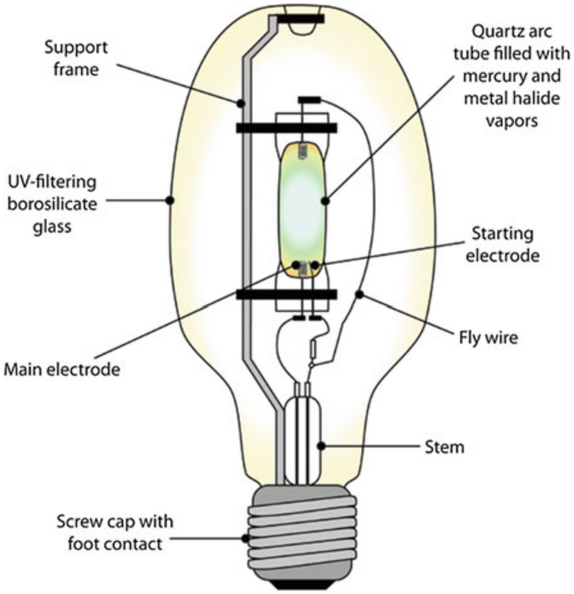


Fig. 1.6 Structure of a high-pressure sodium vapor lamp

Further, the unbalanced spectral quality in relation to the absorption peaks of chlorophyll a, b and β-carotene makes them unsuitable for promoting photosynthesis and photomorphogenesis. Compared to other conventional light sources, HPSLs with high electrical efficiencies of 30–40% are the most energy-efficient light sources used in plant growth.

The metal-halide lamp is a modified version of high-pressure mercury vapor discharge lamp. The inclusion of metal halides along with the mercury vapor and inert gas permits the optimization of the spectral quality of the emitted radiation to a certain extent. Metals such as sodium, scandium, indium, thallium, and dysprosium are used in MHLs because of their characteristic emission spectra in the visible range. Generally, iodides, and sometimes bromides, of these metals are chosen because they are easier to vaporize and ionize than the pure metals as such. Like the other HIDLs, the pressurized gas is maintained within the arc tube and the same mechanism of operation is followed for electron excitation and light emission (Fig. 1.7). However, the outer casing is made of UV-filtering quartz glass to block the UV radiations of mercury. Since the light emitted by the lamp is a mixture of the radiations by the individual metals present in the vapor mixture, changing the combination of the metal halides allows the production of MHLs with various emission spectra (Simpson 2003). MHLs have an evenly distributed spectral output and produce white light with a high luminous efficacy of 100–120 lm/W. MHLs can be used in plant growth applications due to its high PAR, relative high percentage of blue radiation, and energy efficiency of approximately 25%.

Fig. 1.7 Structure of a metal-halide lamp



1.3 Light-Emitting Diodes (LEDs)

LEDs are known as solid-state light sources because they emit light from a semiconductor diode chip. Although the emission of light from ILs also occurs from a solid (filament), the cause of electromagnetic radiations is quite different from the LEDs. The ILs emit radiations due to the heating up of the filament, whereas LEDs emit light due to the transition of electrons from higher to lower energy orbital's. GDLs emit radiations due to release of excess energy from electrons too, but the source of energy is thermionic excitation due to the electric arc. In LEDs, the electrons are not impelled into higher excitation states but simply driven by the electrical potential difference from a higher energy orbital to a lower one. In this section, the major landmarks in the development of LEDs have been briefly outlined and the basic working principle of LEDs pertinent to plant scientists has been discussed.

1.3.1 Development of LED Technology

A LED is a solid-state semiconductor device that emits light upon the flow of electricity (Fig. 1.8), following the principle of electroluminescence. Electroluminescence is the emission of light when electrons driven by an electrical or magnetic field enter a lower energy orbital and release the excess energy in the form of electromagnetic radiations. The phenomenon was first observed by H.J. Round in 1907 while working with silicon carbide (SiC). In 1927, Oleg Losev proposed a theory behind the phenomenon and outlined various practical applications of the technology (Zheludev 2007). Later, in 1955, R. Braunstein reported the emission of infrared radiations from various semiconductor alloys. James Biard and Gary Pittman (1961) of Texas Instruments accidentally discovered the emission of infrared radiations from gallium arsenide (GaAs) semiconductor upon the passage of electricity, while working on solar cells. They patented the design as "semiconductor radiant diode" in 1962, and that was the world's first light-emitting diode (LED). In the same

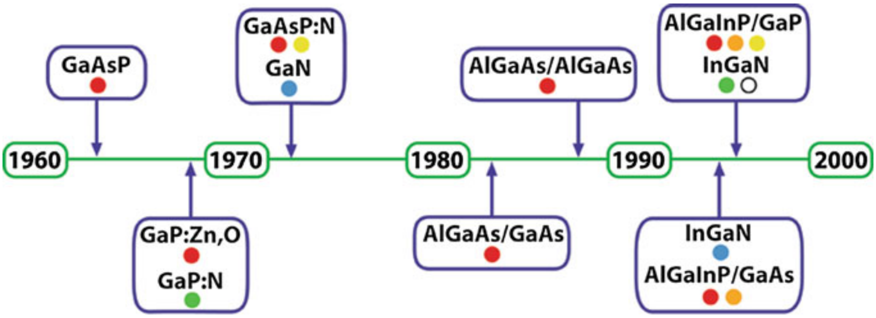


Fig. 1.8 Historical development of semiconductor materials used for LED fabrication

year, Nick Holonyak Jr. designed the world's first LED producing visible light (red) using a gallium arsenide phosphide (GaAsP) diode. Ten years later, Holonyak's student M.G. Craford designed the GaAsP-based yellow LED and high-brightness red and red-orange LEDs. However, the LEDs being produced were too costly and were bright to an extent to be used only as indicators. In 1970, improvements in semiconductor fabrication and packaging techniques by Jean Hoerni and Thomas Brandt led to the drastic reduction in the cost of manufacturing LEDs. Initially, the development of light-emitting semiconductor technology was associated with red and infrared radiations. The lack of a viable blue LED hindered the utilization of this technology to plant growth applications. H.P. Maruska designed the first blue LEDs based on gallium nitride (GaN) in 1972. However, Maruska's LEDs had limited applications due to its low level of brightness. In 1994, Shuji Nakamura presented the design for a high-brightness blue LED employing an indium gallium nitride (InGan) diode. The newly developed LED with a peak emission wavelength of 450 nm was found to be suitable for use in studies on plant growth and development. The wavelength matches with the maximum absorption peak of plant photoreceptors of carotenoids. For this revolutionary invention of efficient blue LEDs which has enabled energy-efficient bright white light sources, the Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura. Over the years, gradual advancements in diode fabrication techniques have resulted in further reduction in the cost and significant increase in the luminous (lm/W) as well as photon (μmol/J) efficiencies.

Various semiconductor materials have been used since Holonyak's GaAsP-based model for fabricating red, green, blue, and white LEDs. Choice of the semiconductor alloy was guided by the need to increase the range of emission wavelength and luminous efficacy of the new LED as compared to its predecessors. The historical development of semiconductor material systems associated with improved performance of LEDs in terms of luminous efficacy is shown in Fig. 1.8. Further enhancement in luminous output and power efficiency could be attained by increasing the efficiency of radiative recombination (electron–hole pairing leading to photon emission) within the LEDs. This was achieved via bandgap engineering by the use of heterostructures and quantum wells. Advancements in epitaxial crystal growth techniques enabled the formation of customized heterostructures and quantum wells in LED chips (Schubert 2003). The technology led to the development of power-efficient high-brightness LEDs that have sufficient luminous output with desired wavelength to sustain optimal plant growth. Such LEDs are made from binary direct bandgap alloys from groups III–V elements of the periodic table, namely aluminum gallium arsenide (AlGaAs), aluminum gallium indium phosphide (AlInGaP), and aluminum indium gallium nitride (AlInGaN). Availability of high-brightness LEDs with spectral output matching with the action spectra of photosynthesis and photomorphogenesis created the platform for the LED-based plant illumination system (Tamulaitis et al. 2005).