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Chad E. Finn

Dedication: Chad E. Finn

Volume 43 of *Horticultural Reviews* celebrates the exceptionally productive career of Dr. Chad Elliott Finn. One of the five kids of D. Francis "Mickey" and Gabrielle "Gay", Chad grew up in Potomac, Maryland in the Washington, DC area. He spent much of his youth exploring the local creek, took over the family vegetable garden at age 10, and a couple of years later had a "eureka moment" when perusing the Burpee Seed Co. catalogue as he realized people could actually have a career developing new cultivars. He attained his B.S. degree in horticultural production at Purdue University (1983) where he was fortunate to be taken under the wings of Jules Janick, Frank Emerson, and Dick Hayden. During his summers away from Purdue, he received his first taste of berry research working under the guidance of renowned breeders Gene Galletta and Arlen Draper. He obtained M.S. (1986) and Ph.D. (1989) in horticulture with a minor in plant breeding from the University of Minnesota, where he was James Luby's first graduate student. His M.S. research focused on the inheritance of late bloom and early ripening in northern highbush, lowbush, and half-high blueberries. He was co-advised by soil scientist Carl Rosen for his Ph.D. thesis, and identified and characterized the response of *Vaccinium* species to varying pH levels and the interaction between pH level and nutrient uptake.

Chad's first career stop was at the University of Missouri where he served as State Fruit Extension Specialist from 1989 to 1993 working with home gardeners and commercial fruit growers. Growers Bob and Ronnie Hershey were introduced to Chad at a chilly blueberry field day and described him as the "redhead with an infectious smile" and recognized a young man enthusiastic about his job. They later visited the home of Chad and wife Barbara Fick and their sons Elliot and Ian, and marveled at the grapes, berries, fruit trees, and flowers reflecting their joint love affair with plants. Chad, sometimes referred to the "fruit geek," is in reality one of the greatest small fruit breeders in the United States.

After his stint in Missouri, Dr. Finn took over the leadership of the USDA-ARS small fruit breeding program in Corvallis. This was a "dream job" for Chad, and he has lived his dream, developing what is probably the most diverse berry breeding program in the world with significant efforts in the major small fruit crops. Initially, he developed very active programs in germplasm and cultivar development for strawberries, blackberries, and red raspberries. More recently, in response to grower input, he added blueberries and black raspberries to his portfolio of breeding programs. Dr. Finn's germplasm development program is the largest and most productive of its kind in the world, extending from collection and evaluation of traits in wild species to incorporation of desirable traits into new cultivars. He has developed cooperative research with other breeders, other scientists for trait evaluations, commodity groups, and growers in the Pacific Northwest and throughout the world.

Dr. Finn led or co-led collection trips for germplasm in the Pacific Northwest, Ecuador, China, and the eastern United States and for *Rubus* and *Vaccinium* materials and incorporated new valuable traits into his breeding materials. He has cooperated with colleagues at various universities to evaluate *Fragaria* germplasm leading to a greater characterization of wild species and the discovery of new traits for cultivar development. The research on *R. occidentalis* from eastern North America has identified multiple sources of aphid resistance, Verticillium tolerance, and novel anthocyanin profiles, which he is now incorporating into cultivar material. The goal is to minimize the impact of Verticillium wilt and aphid transmitted viruses, which have reduced the productive life of black raspberry plantings in the Pacific Northwest to 2–3 years.

Dr. Finn has developed a multipronged approach in many of his breeding programs through collaborations with other scientists, including molecular biologists, food/flavor chemists, plant pathologists, virologists, horticulturists, and other breeders. In this way, he has been able to evaluate a wide range of traits and develop molecular markers for traits of interest in the berry crops. These efforts have been funded through the Specialty Crops Research Initiative (SCRI) grants program, with major efforts on strawberry through RosBREED, and a blueberry and two *Rubus* grants. He led a black raspberry SCRI grant, which was funded based on the preliminary work he and his student did on germplasm evaluations.

Dr. Finn has released or co-released (with USDA, Agriculture and Agri-Food Canada, Washington State University, and University of Arkansas) 37 new cultivars including 11 trailing, 1 semi-erect, and 2 primocane-fruiting, erect blackberries, 8 red raspberries, 11 strawberries, and 4 blueberries, as well as 2 germplasm releases. Among the most important of his many cultivar releases are five thornless blackberries, and ‘Black Diamond’ has been the most widely planted blackberry in the Pacific Northwest in recent years. The latest, ‘Columbia Star’, is anticipated to be as good as or better than ‘Marion’, the processing industry standard. Fruit sales from cultivars that Dr. Finn has released were greater than $120 million over the past 5 years.

Dr. Finn has authored or co-authored 162 scientific papers, 6 patents/patent applications, 30 book chapters, 34 extension publications, 89 proceedings, and over 85 abstracts as well as given over 180 invited presentations. Dr. Finn has obtained, with teams, over $14 million in competitive grants with over $3.75 million going to his program. The innovativeness and impact of Dr. Finn’s research program have been recognized by the scientific community and small fruit industries as demonstrated by his election as Fellow in the American Society for Horticultural Science; Distinguished Alumni Award from the Department of Horticulture, Purdue University; a USDA-ARS Technology Transfer award; Wilder Medal by the American Pomological Society; and numerous international and domestic requests received for information, invitations to discuss his research programs, successful grant proposals, and requests to assist in development and evaluation of plant materials from other breeding programs. He is a courtesy professor in the Department of Horticulture at Oregon State University and has supervised/mentored 6 M.S. and 2 Ph.D. students and has served on 15 graduate student committees.

Dr. Finn is recognized internationally as a leading authority on small fruit crops, especially in the areas of breeding, germplasm, and cultivar performance as well as in production and processing. He has hosted visiting scientists from Argentina, Australia, Canada, Chile, China, Ecuador, France, Germany, Greece, Italy, Japan, Korea, Mexico, the Netherlands, New Zealand, Pakistan, Poland, Portugal, Russia, Serbia, Scotland, Serbia, South Africa, Spain, Sweden, Turkey, Ukraine, and United Kingdom, as well as U.S. scientists from more than 30 states. Dr. Finn is also active in the American Society for Horticultural Science (ASHS) and the International Society for Horticultural Science (ISHS), serving in Working Groups and on the Scientific Committees for the publication of the *Acta Horticulturae* for *Rubus* and *Ribes*, *Vaccinium*, and strawberry symposia since 2001. He has given invited keynote addresses at the *Rubus* and *Ribes* (2001, 2005) and *Vaccinium* (2012) Symposia of ISHS and was co-convener of the ISHS *Vaccinium* Symposium held in Corvallis in 2008 and the ISHS Berry Fruit Symposium held in Brisbane, Australia. He has been invited to present his research results in Argentina, Brazil, Canada, Chile, China, Italy, Mexico, the Netherlands, Scotland, United Kingdom, Uruguay, and at multiple universities, grower's meetings, and ASHS meetings in the United States. Dr. Finn has been involved in the Small Fruit Crop Germplasm Committee for the USDA-ARS National Plant Germplasm System since 1993. He is a member of the American Pomological Society, having served on advisory committees from 1996 to 1998 and on the Executive Board since 2011. He served as co-editor for the American Pomological Society/ASHS Fruit and Nut Cultivar List for 2005–2012 and as registrar/contributor for the List for blackberry and hybrid berry (1999–2014) and strawberry (1999–2009). He also served as co-editor for the *Journal of Berry Research*.

One of the Chad's closest colleagues at Oregon State University, Dr. Bernadine Strik, offers the following tribute: "Chad is the kind of colleague you dream about—one who is very passionate about his job, hardworking, giving, fair, innovative, and productive. He does his job with a sense of humor and no matter what the circumstances, he makes people feel at ease; he is a great speaker—knowledgeable, humorous, and animated; he is extremely well respected by peers and industry nationally and internationally. I couldn't imagine a better collaborator and friend."

Fellow USDA-ARS researcher and Research Leader (Chad's boss) for the Horticultural Crops Research Laboratory at Corvallis, Dr. Robert Martin, comments: "Chad is a bright, optimistic, jovial, helpful, enthusiastic colleague and friend. We have worked together on many projects and he is a great collaborator in every respect. Although unlike Bernadine, I don't dream about him." Dr. Martin and Chad share enological enthusiasm along with their annual vintage of "Bottled Optimism."

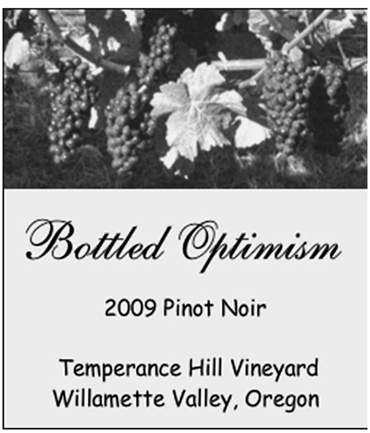
Another longtime colleague, Jim Hancock at Michigan State University, shared his relationship with Chad: "I have worked closely with Chad for probably 25 years on a wide array of projects involving small fruit genetics, and seen him in action with growers, marketers, and scientists. Simply stated, he is a tremendous joy to work with and is the consummate professional. He is thoughtful, caring, articulate, thorough, willing, dependable, productive, and a particularly fine human being. The small fruit community is a much better place because of his accomplishments and warm, giving personality."

Dr. Finn has had a worldwide impact. Professor Bruno Mezzetti of Universitá Politecnica delle Marche, Ancona, Italy shared that he can "surely confirm his recognition as an international leader in the field of genetic and breeding studies applied to all major berries." Dr. Mezzetti further comments "For his personality, friendship, and sincerity, I consider Chad one of the greatest colleagues and collaborators ever, and hope to have more cooperation in the future."

Dr. Rex M. Brennan of the James Hutton Institute, Invergowrie, Scotland is another admirer of Dr. Finn. "I've known Chad for more than 20 years, and have the greatest admiration for him and his achievements in fruit breeding. He has a tremendous depth of knowledge about germplasm and breeding, and can both apply and communicate these things in an inspirational way. I know he takes very seriously the mentoring of younger people starting out in the fruit breeding world. Chad is so generous with his knowledge and with his time—not just with people like me but with absolutely everyone. He treats everyone with the same generosity of spirit. And as I am sure everyone will say, he's a really great guy to spend time with, in person or even just on email!"

From Chile, Dr. Jorge Retamales with the University of Talca: "Chad and I have interacted 'fruitfully' for more than two decades on small fruit crop physiology and breeding. The most outstanding characteristics of Chad are his wisdom and happiness . . . he has taught us that the joy is not only found in reaching the target, or the finish line (i.e., published paper or registered cultivar), but throughout his life Chad has shown us that the process of doing research in horticulture can be (and should be) exciting and a joy. I feel blessed for having Chad as a colleague and friend. He has been a light that shines very brightly and leads us to excellent and enjoyable science (as well as life in general)."

Dr. Chad Finn has achieved an immense amount in his career, a result of his love for his family, friends, colleagues, and the plants he cherishes. All who come in contact with Chad Finn recognize that he is special. He continues to inspire horticulturists everywhere.



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Light-Emitting Diodes in Horticulture

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ABSTRACT

Light-emitting diodes (LEDs) have great potential to revolutionize lighting technology for the commercial horticulture industry. Unique LED properties of selectable, narrow-spectrum emissions, long life spans, cool photon-emitting surfaces, and rapidly improving energy use efficiency encourage novel lighting architectures and applications with promising profitability potential. In greenhouses, such unique properties can be leveraged for precise control of flowering and product quality for the floriculture industry, for energy-efficient propagation of ornamental and vegetable transplants, and for supplemental lighting of high-wire greenhouse vegetable crops for all-year production. In a sole-source lighting mode, LEDs can also be used for transplant production, as well as for production of rapid-turning vegetable and small fruit crops. Evidence is accumulating that nutritional and health attributes of horticultural products may be enhanced by specific wavelength combinations of narrow-spectrum light from LEDs. During periods of seasonally limited solar light, LEDs have potential to enhance daily light integral in greenhouses by providing supplemental photosynthetic radiation, particularly of red and blue light. The cool photon-emitting surfaces of LEDs permit their novel placement relative to crop foliar canopies, including close-canopy overhead lighting as well as within-canopy lighting, which greatly reduces electrical energy requirements while maintaining adequate incident photon fluxes. Because of the small size of individual LEDs and narrow beam angles from LED arrays, light distribution can be highly targeted and waste of light from LEDs minimized compared with other light sources traditionally used for horticulture. Prescriptions of spectral blends (e.g., red:far-red and red:blue ratios) can be developed for LEDs to accomplish specific photomorphogenic goals for seedling development, flowering, and possibly yield and produce quality. LED light quality may also be useful to control pest insects and to avoid physiological disorders otherwise caused by low-intensity or narrow-spectrum lighting. Complex factors such as rapidly improving LED luminous efficacy, favorable mass-manufacturing costs, local costs of electrical energy, and capital investment will interact to determine for which applications and when LEDs become the dominant lighting technology in horticulture.

KEYWORDS: energy savings; greenhouse; intracanopy; light quality; night interruption; photomorphogenesis; photoperiod; propagation; sole-source lighting; solid-state lighting; supplemental lighting

ABBREVIATIONS

ABRS	Advanced Biological Research System
AC	Alternating current
ASHS	American Society for Horticultural Science
B	Blue
BF	Blue fluorescent
CEWG	Controlled Environments Working Group
DC	Direct current
DE	Day extension
DIF	Day temperature – night temperature
DLC	Dynamic lighting control
DLI	Daily light integral
DOE	Department of Energy
DPPH	2,2-Diphenyl-1-picrylhydrazyl
EOD	End of day
ESD	Electrostatic discharge
FL	Fluorescent
FR	Far-red
G	Green
HID	High-intensity discharge
HPS	High-pressure sodium
HR	Hyper-red
IC	Integrated circuit

ICL	Intracanopy lighting
INC	Incandescent
ISS	International Space Station
kWh	Kilowatt hour
LD	Long day
LDP	Long-day plant
LED	Light-emitting diode
lm	Lumen
MH	Metal halide
NASA	National Aeronautics and Space Administration
NBL	Narrowband lighting
NCERA-101	North-Central Extension and Research Activity-101
NI	Night interruption
OH	Overhead
PAR	Photosynthetically active radiation
PBB	Polybrominated biphenyl
PBDE	Polybrominated diphenyl ether
P_{FR}	Far-red-absorbing form of phytochrome
PPF	Photosynthetic photon flux
P_R	Red-absorbing form of phytochrome
PS	Photosynthesis
PWM	Pulse-width modulation
QI	Quality index
R	Red
RDM	Root dry mass
RWB	Red + white + blue
SD	Short day
SDP	Short-day plant
SL	Supplemental lighting
SPAD	Relative chlorophyll content
SSBRP	Space Station Biological Research Program
UV	Ultraviolet
VOC	Volatile organic compound
W	Watt
WF	White fluorescent

I. INTRODUCTION

Horticultural lighting long has borrowed technology from the lighting industry that was not originally designed or intended for plant growth and development. As a consequence, horticulturists and plant physiologists learned to "make do" with the range of lamps that were available for supplemental or sole-source lighting of horticultural crops. Incandescent lamps became the standard for photoperiod control in greenhouses (Downs et al. 1958). Fluorescent (FL) ± incandescent (INC) lamps were widely used to achieve "normal" plant growth and development in growth chambers (Biran and Kofranek 1976; Bickford 1979), and when high-intensity discharge (HID) lamps came along, they quickly became the standard for supplemental lighting (SL) in greenhouses and for sole-source lighting in phytotrons and some growth chambers (Warrington et al. 1978; Tibbitts et al. 1983). All of these light sources do the job, but also have serious limitations. At the time they were adopted, there were no good alternatives. Incandescent lamps are highly wasteful of energy, are very short-lived (Bickford and Dunn 1972), and are rapidly disappearing from the marketplace. Fluorescent lamps have limited photon output and a short effective life span (Sager and McFarlane 1997). High-intensity discharge lamps require high voltage, emit intense radiant heat (McCree 1984), and require wide spatial separation from plants and/or thermal barriers. Light-emitting diodes (LEDs) were first tested with plants more than 20 years ago (Bula et al. 1991; Barta et al. 1992), and a revolution in lighting technology for horticulture has been underway ever since. This chapter compiled by a multi-institutional team of researchers investigating the feasibility of adopting LED technology for commercial specialty crop production (Mitchell et al. 2012) summarizes the state of knowledge regarding LED technology for horticulture and plant responses to various spectral combinations of LED lighting as of 2015.

II. PROPERTIES OF LEDs

A. What Are LEDs?

An LED is a light source that, unlike traditional lamps, does not use a filament or gas discharge. Illumination is produced solely by movement of electrons in a semiconductor material (Held 2009). Electrons cross a semiconductor junction and recombine with electron holes, releasing energy as photons (electroluminescence) in a narrow waveband. The color of a specific LED is determined by the energy gap of the semiconductor used, which is based on the semiconductor chemical composition.

LEDs are available in a variety of wavebands ranging from the ultraviolet (UV)-C (about 250 nm) to the near-infrared range (about 1,000 nm), with half-peak bandwidths generally ranging from 25 to 50 nm. Broad-spectrum white LEDs are also available—these create white light by using a blue (400–500 nm) LED combined with a phosphor coating. LEDs can also be used to create white light by mixing appropriate amounts of light from individual red (600–700 nm), green (500–600 nm), and blue LEDs.

Unlike traditional lamps, LEDs do not radiate heat directly in the light beam. However, a significant amount of heat is still produced and this heat must be conducted out of the device to prevent premature failure. Modern, high-power LEDs have a thermal pad directly connected to the light-emitting (and heat-generating) substrate. This pad moves heat from the junction to the solder point, through the circuit board, and to the heat sink by conduction, and then from the heat sink to the environment by convection and radiation.

B. LEDs as a Horticultural Lighting System

Solid-state lighting using narrow-waveband LEDs represents a fundamentally different technology from the broad-spectrum gaseous discharge-type lamps currently used in horticulture (Sager and McFarlane 1997). The semiconductor nature of LEDs makes them potentially one of the most significant advances in horticultural lighting since the development of HID lamps (Morrow 2008). The specific advantages of LEDs include capability to control spectral output and light intensity and to provide high or low light levels. Because LEDs can be rapidly turned on and off, and easily incorporated into electronic circuits, they can respond to complex control protocols. LEDs also provide the potential for reducing lighting operational costs through their long operating life and ability to operate directly adjacent to plant tissues due to their low radiant heat output (thereby reducing power use). Light-emitting diodes lack glass envelopes and toxic materials such as mercury, have low touch temperatures, and generally are operated at low direct current (DC) voltages, making them safer than current lamp types. Other benefits include their thin cross section, rugged construction, and flexibility for assembly into lighting systems with specialized configurations. Their use of DC would be an advantage in a setting using DC power generated from alternative power systems such as batteries or solar panels.

Disadvantages of LEDs compared with existing lamp types include currently high hardware costs. Since LEDs operate most effectively using DC, implementation requires conversion of standard alternating current (AC) to DC (using AC-to-DC power converters).

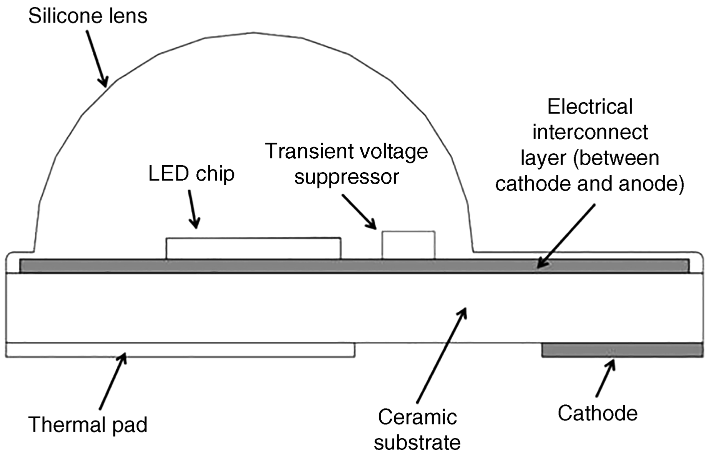

Fig. 1.1. Cross section of example LED package, about 2 mm × 3 mm in size. This package is designed to be soldered to a circuit board. The ceramic substrate provides a means to remove heat from the LED chip through the thermal pad to the circuit board. The transient voltage suppressor protects against electrostatic discharge and the silicone lens shapes light and shields the chip.

C. LED Packaging

Light-emitting diode lighting systems are generally used as groupings of many individual LED devices, each device being approximately 2 mm × 3 mm in size. The device includes the actual LED semiconductor chip, a lens, and components to provide mechanical support and transfer of heat away from the chip. Components are included to allow integration of the LED into an electronic circuit (Fig. 1.1).

D. Wavebands of Interest

Several wavebands of interest to horticulturists are available in LEDs (Olle and Virsile 2013). Commonly available red wavebands include 627 and 660 nm, whose spectra are close to the maximum chlorophyll absorption peak. Red light of 660 nm also matches a phytochrome absorption peak, as does 735 nm. Ultraviolet and blue wavebands, including 365, 400, 450, and 470 nm, are absorbed by cryptochrome pigments, which also impact plant development and physiological functions. Green wavebands (i.e., 540 nm) may have some utility due to improved foliar penetration increasing canopy photosynthesis. Other colors are used for specialized functions such as providing excitation for visualization of fluorescing proteins. In addition, several phosphors are available that can be used with blue LEDs to provide broader spectrum light in a variety of colors (Mills 2004), which is the primary technique used to produce white LEDs.

E. Performance Trends and Outlook

Light-emitting diode technology (both for research and for general area lighting in homes and businesses) has improved significantly in terms of physical shapes and designs, number of color wavebands available, reduced power use per unit light output, higher light output per unit power input, and reduced cost per unit light output (Morkoc and Mohammad 1995; Norlux Corporation 2004; Philips Lumileds Lighting Company 2004, 2005, 2006, 2007, 2008a, 2011, 2012/2013). The technical development of LEDs is said to follow Haitz's law, named after Dr. Roland Haitz, who states that every decade the cost per unit of useful light emitted for a given waveband of light falls by a factor of 10 and the amount of light generated per LED package increases by a factor of 20 (Haitz et al. 1999; Haitz and Tsao 2011). LED lighting applications may ultimately be limited by market forces (e.g., achievable light levels are already in excess of what is needed to meet large commercial market requirements).

F. Misconceptions About LED Lighting

With the great interest in LED lighting systems, a number of misconceptions about their capabilities have become commonplace. One of the primary misconceptions is about LED inherent luminous efficacy. It is widely discussed how much more efficient LEDs are than currently used lamp types. Interestingly, this has been a common statement for many years, even when LED efficiency was actually substantially less than current sources (whose efficiency has also improved over the last several years), and it is only recently that some LED devices (e.g., blue LEDs) are approaching or exceeding the best of the fluorescent and high-intensity discharge lamps (Nelson and Bugbee 2014). Although LEDs are projected to exceed all other current lighting technologies in the next few years (DOE 2013a), it should be emphasized that the potential for large improvements in power efficiency in horticultural settings is not so much related to the LED semiconductor die composition per se, but to the fact that their solid-state nature and physical characteristics allow implementation of unique configurations and operating protocols that can bring about large efficiency gains (Fig. 1.2).

Efficiency of a specific LED package (a single LED with mount) is related to factors such as semiconductor composition and doping, and mounting package configuration (DOE 2014). Efficacy of an LED package differs for each color, with blue LEDs being most efficient, while other

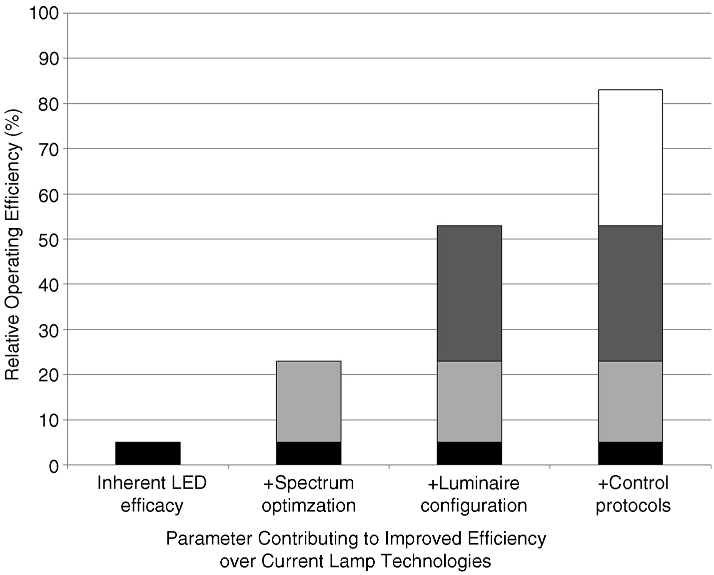

Fig. 1.2. Stacking different LED attributes illustrates the potential for developing LED horticultural lighting systems with very high operational efficiency (numbers are approximate and shown as additive for illustrative purposes). Refer to the text for detailed explanation for basis of graph.

colors, such as green, have room for improvement. Increases in photosynthetic efficiency by matching wavelengths to chlorophyll absorption peaks have been shown in some plant testing (Stutte et al. 2009). Luminaire configuration relates to reflector design, lenses, how the LEDs are arranged, and how the luminaire is positioned (operating in close proximity to plants can significantly reduce light loss because it is falling on walls and walkways rather than on plant tissue) (Morrow 2008; Nelson and Bugbee 2014). Control protocols can also be used to optimize energy consumption. For example, control protocols have been developed that detect the locations of plant tissue and only provide light to those locations (Massa et al. 2005b; Morrow and Bourget 2009).

Another common perception is that LED systems have an extensive operating life. While manufacturer's literature provides a conservative figure, often around 50,000 h of operation (DOE 2006), the actual life of the devices is dependent on a number of parameters when used in a real system. The output and operating life of an LED can be adversely impacted by high LED junction temperatures, poor current regulation, manufacturing quality (e.g., soldering quality), component quality, excessive shock and vibration (though LEDs are more resistant to shock