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Review

Light, what it is and what it does for mycology

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ABSTRACT

With the exception of photosynthesis, the importance of light is often forgotten by biologists. However, light is of great importance for many aspects of basic and applied mycology, particularly for mushroom cultivation. Infrared can be used to help identify chemicals produced by fungi. A common use of infrared is monitoring and controlling the gas environment, particularly carbon dioxide. We all need visual light for our everyday activities. Visible light has been shown to be required for the production of mushrooms, with the prominent exception of *Agaricus*, the genus of the common commercial mushroom. Yet, there have been very few publications on mushroom cultivation that indicate any real understanding of light. More meaningless than meaningful data have been published on light conditions for mushroom cultivation. We can not see ultraviolet light, but publications dealing with ultraviolet and fungi generally indicate some knowledge of it. We might say, the light we experience most is what we know least of. Most basic studies on the effects of light on fungi have been carried out in model organisms (*e.g.*, *Neurospora*, *Coprinopsis*, *Schizophyllum*) showing that a variety of photoreceptors are involved, but their practical implications are not yet available. The internet and textbooks are sources of extensive information on what light is and how it can be used in the laboratory. However, there is little information, on visible light, that applied directly to mycology. In this review we

attempt to give readers a basis for understanding what has been learned, what we know or we do not know, and some things that can be done with what we do know. Information on detecting CO_2, H_2O, ethylene, methane and ethane, as well as the internet address to find much more, is given. Characteristics of visible light are discussed. The need for mushrooms to have blue light is indicated. The conversion of the fungal steroid, ergosterol, to vitamin D_2 and ultraviolet as a means of killing bacteria, fungi and human cells is discussed.

Key words: Basidioma, ergosterol, gas monitoring, infrared, photoreceptors, ultraviolet, visible light, vitamin D_2.

INTRODUCTION

First, it should be clear to all that a thorough review of the subject of light would be a very large tome. Also, we have known many things about light for centuries, so it would be a history. Yet, there remains much to learn about the biological activities of light. The purpose of this review is to make the subject better understood, and to cover all of the areas that we know affect mushroom cultivation and consumption. Of course, things that affect the cultivator affect the cultivation. Maybe optics for cameras, microscopes and eyeglasses would be appropriate for many readers. Also, the colors of mushrooms might add interest. However, there are textbooks on optics and on color, and we could not begin to compete with their authors.

We all think we know what light is, but there might be some surprises. So first, let us look at the big picture, the electromagnetic spectrum. The University of California has a representation, **Fig. 1**, that tells us it fits in between radio waves and gamma rays[25]. Notice that there are three kinds of light shown, infrared, visible and ultraviolet. All of those and some other electromagnetic radiation, come to us and to wild mushrooms from the sun. This review is only about light, so the remainder of this review will be broken down into infrared, visible and ultraviolet light.

Since the first light that affects the mushroom and the cultivator, at least historically is sunlight, that is the natural reference for this review. Sunlight is 40% at wavelengths of infrared (IR) or longer, 50% at visible wavelengths, and 10% at wavelengths of ultraviolet (UV) or shorter (think: skin penetration)[25]. **Fig. 2** shows a light spectrum of the sun both in space and at the surface of the earth. Note that the intensity is rated in Watts per square meter per nm. Output Watts are the primary way that light scientists measure light. Input Watts per hour are what you see printed on an electric light and since all electric lights use only a little of the input energy to produce light, there is little relation between the input and output numbers. In the sections that follow, we will try to expand on these thoughts and clarify a variety of the properties of light.

INFRARED LIGHT

If we go by **Fig. 1**, infrared is the first light from the top, but if we go by **Fig. 2**, ultraviolet is the first light on the left. We

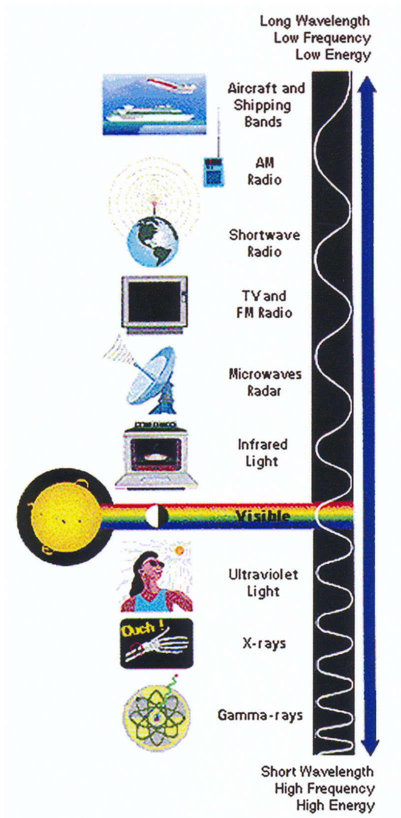

Fig. 1. An overall representation of the electromagnetic spectrum[25].

are going with the order suggested by **Fig. 1**, partly because it suggests that infrared is a wide band of wavelengths. Not only does infrared cover a much broader range, but it is the most ubiquitous radiation. All light of wavelengths greater than 780 nm is usually considered infrared. However, between 780 and about 3000 nm it is referred to as near infrared. **Fig. 2** shows four bands in the near infrared where sunlight has been absorbed at earth's surface compared to the top of the atmosphere. Those four bands represent absorption by water vapor[23].

Everything radiates infrared in proportion to their temperature. Infrared thermometers have become common items. **Fig. 3** is an inexpensive unit that is convenient for determining temperatures of surfaces. It can find a warm or a cold wall in a building or an incubator, a cold spot in a compost pile or any other surface. Of course it will not tell the temperature inside an object. Such surface measurements can be very useful in mycology, but especially in mushroom cultivation.

Infrared spectrophotometers are much more sophisticated. They may look at 3000 to 22000 nm so a considerable range to the right of **Fig. 2**. Most things absorb one or several wavelengths of infrared. Spectrophotometers can be used to identify chemicals and to determine the quantity[16]. For routine or continuous determinations, devices that are set to one wavelength are also available and can measure gas or liquid that moves through them. Several gases are of wide biological interest. Carbon dioxide absorbs primarily at 2700, 4300 and 14900 nm[16]. Water absorbs in the near

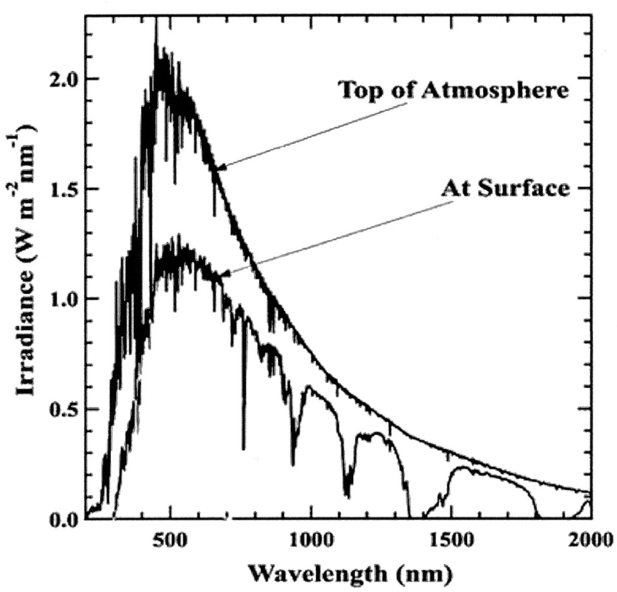

Fig. 2. The visible and near infrared spectrum of the sun. Irradiation is in Watts per square meter for one nanometer wave length increments[26].

Fig. 3. An inexpensive hand-held infrared thermometer.

infrared[23] and at 3000, and 6100 nm with a strong broad band from 14500 to 26000 nm and into the microwaves[16]. Methane is produced by many anaerobic organisms; it absorbs at 3300 and 7700 nm[16]. Methane and ethane may be of research interest, but their importance is less well established in mycology. Ethylene is produced by green plants, by mushrooms[22,27], and other fungi[15]. Apparently it helps regulate basidioma formation[11,22]. Ethylene absorbs at 3300, 5300, 6900, and 10000 nm[16].

Infrared carbon dioxide sensors are in common use where sophisticated equipment is in use for mushroom growing. Infrared is not in common use for humidity monitoring, but it has a faster response than any other humidity detector. It is far more reliable at high humidity than common humidity meters. It requires less maintenance than an electronic wet-bulb thermometer.

There can be no question that the carbon dioxide in our atmosphere is increasing and that higher carbon dioxide is causing problems. Both scientists and farmers who are concerned with mushroom cultivation must be concerned with increasing carbon dioxide in the world's atmosphere. As atmospheric carbon dioxide increases, more ventilation will be required to dilute the carbon dioxide in mushroom growing buildings. Mushrooms are particularly sensitive to carbon dioxide, poor quality ventilation is often the cause of reduced mushroom production. Atmospheric water vapor aids mushroom production, it has not been shown to increase, and yet infrared spectra tell us it absorbs more heat than carbon dioxide[23]. Its effects are so great that a cloudy day will be cooler, but a cloudy night will be warmer than expected with clear skies. Further, when carbon dioxide is produced, heat is produced. Our own bodies warm themselves by oxidizing carbohydrates, and other things that we eat, to carbon dioxide and water. A question to ponder is, are we ignoring a very important part of global warming and how does it affect various needs of mushrooms?

We can add other ways in which infrared is used in our lives, for example, remote controls with infrared lasers for cameras and projectors. Also the infrared laser in a TV remote that sends the viewer's desires to the TV. However, TVs are generally not of mycological interest.

VISIBLE LIGHT

Visible light is of importance for almost everything we do. We want to see where we are going, see to read, etc. When we see a rainbow, we see the light of the sun, broken into its colors. The Kitt Peak Observatory has posted the sun's spectrum as a colorful photo made up of 100 lines each incrementing by 6 nm[9]. Yet, how much do we know? Intensity? Color – cool or warm? Wavelength? ºK? **Fig. 2** gives some idea of wavelength, so maybe best to start with ºK. The sunlight is about 5200 ºK[24]. We see ºC or maybe ºF all of the time, but we seldom see ºK, or just K, except on electric lights. Another name for K is absolute temperature and it is equal to ºC plus 273.15º. We were discussing light now suddenly temperature! Well, 5200 K is the theoretical temperature of a "black body" that will radiate light of the same color as the sun. In effect, the filament of an ordinary incandescent light is a black body that electric power heats to about 2500 to 3000 K. So, a "warm" LED (Light-Emitting Diode) or fluorescent light will be labelled 2700 K and a "cool" one 5000 K. **Fig. 4** is a photo of five different bulbs. We can see that the three center lights (2700 K) give us less blue than the two outer bulbs (5000 K). Some other values of interest: the sunlight on cloudy days, 6000 K; in the shade 8000 K[24]. Most wild mushrooms grow in the shade. Of course, as used for light "warm" and "cool" are backwards. However, people associate red with hot and blue with cold, maybe they think of their skin color, or the apparent color of ice and red is the color seen when the blacksmith heats metal in a forge, or when we heat an inoculating "loop" to sterilize it for transferring a culture to fresh agar. It should be pointed out that there is a great difference between the colors we see on solid objects and the colors of light. There is an extensive discussion of the difference and use of RGB vs. CMYK in the Corel Draw books[3].

Maybe the absorption spectrum of chlorophyll is appropriate, in that fungi

Fig. 4. Left to right: 5000 K LED light, 2700 K fluorescent light, 2700 K LED light, incandescent light, 5000 K fluorescent light. All lamps are "60 Watt (incandescent) equivalents," that is, 800-850 lumens.

are associated in a variety of ways with plants **Fig. 5**. Also, there is an important interaction of mushrooms with plants, to be discussed later, where the spectrum is of interest. Chlorophyll is green, but we can see that it absorbs almost no green light. It is green because it reflects green light. It uses red and especially blue light as sources of energy. Ice (and water) absorb more of other colors, and reflect blue, so we think of them as blue.

Another source of confusion is terminology used in describing light intensity. The lumen (symbol: lm) is the international unit of luminous flux. It is the visible light emitted from an opening of 1/16th cm^2 in a standard source[21].The standard source is further defined, but is a black body at the melting point of platinum

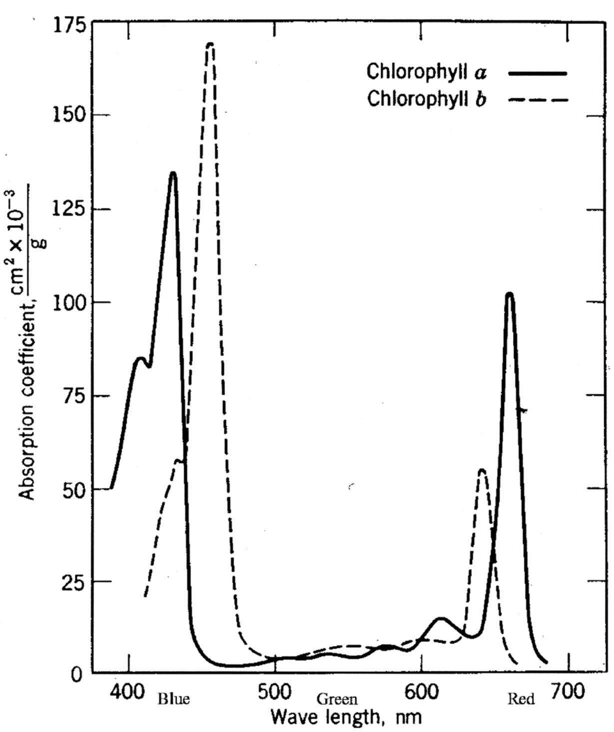

Fig. 5. Visible light spectra of chlorophyll *a* and chlorophyll *b*[5].

or 2047 K[14]. That is about the same color as the flame of a wax candle. Lux may be described as "the illumination per square metre of a surface at a distance of 1 metre from a point source of 1 candela (1 lumen)"[13]. So lux refers strictly to visible light, measured on the surface of interest, and it is referred to a yellow standard. It is important to realize that all light is attenuated by the square of the distance from the source. That means that it is very difficult to have even illumination over any practical mushroom growing conditions.

We can also find other confusing definitions, but the important point is that the lumen and the lux are measurements of what the human eye sees. So it is useful to evaluate lighting to be used for human activity. It is also useful for photography and with similar activities that wish to represent what people see. However, silver based film is more sensitive to blue and to some degree, modern CMOS sensors tend to mimic film, but with more control. For that reason, when studies wish to describe light activity that is unrelated to the human eye, watt or other strict units of energy are used for measurements. Lux appears in many publications on mushroom cultivation. It has limited meaning if the light source is described, but has no meaning if we do not know the light source. **Fig. 6** shows us what one watt of energy means to our eyes at all wavelengths of visible light. While one watt of green light at 555 nm gives us nearly 700 lumens, one watt of violet light at 400 nm or one watt of red light at 700 nm provides our eyes with zero lumens, hence zero lux.

A publication by Kaufert in 1936 seems to be the first indication that *Pleurotus* required light[8]. In 1960, Aschan-Aberg showed that blue light was required for basidioma of *Flammulina velutipes* (enokotaki)[1]. Carlile noted that blue light between 400 to 480 nm was required for all *Coprinus* species that had been tested[2]. Only 3 μW/cm² of light passed by a Corning C.S. #5-58 filter (360 to 460 nm) was required to produce normal *P. sapidus* basidioma[12]. Most basic studies on the effects of light on fungi have been carried out in model organisms, such as *Phycomyces blakesleeanus*, *Neurospora crassa*, *Aspergillus nidulans*, *Coprinopsis cinerea*, and *Schizophyllum commune*. Recent advances in fungal photobiology using molecular tools and genomic analysis have shown specific phytochromes, photoreceptor proteins, transcription factors, light-regulated genes, and to a certain extent common regulatory pathways leading to mushroom development and spore viability. Several blue-light and red-light absorbing photoreceptors receive photons and transduce the photon energy into the cell to regulate fungal photoresponses through differential gene expression, *e.g.* carotenoid biosynthesis, hyphal aggregation, primordia formation, and mushroom differentiation[4,18]. Similar processes are expected to occur in commercially cultivated mushrooms, such as *Pleurotus*, *Lentinula*, and *Ganoderma*. Light-regulated genes seem to be widespread in fungal genomes, showing the relevance of light not only in fungal metabolism, but also in sexual and asexual development[7,17].

It seems likely that all mushrooms, which require light, use a common regulatory pathway for basidioma development. However, interesting is the case of those species that do not require light for fruiting, such as *Agaricus bisporus*, because it is not known yet if they have inactive light absorbing photoreceptors or alternative mechanisms. Then we can expect that the active photoreceptor(s) absorbs light between 480 and 460 nm and **Fig. 6** suggests that we can expect 150 to 200 lumens per Watt in that waveband. Looking back at **Fig. 5**, we notice that chlorophyll *a* does not absorb those wavelengths, while chlorophyll *b* absorbs between 5 and 100 on the absorption coefficient scale. Since most mushrooms known to require light are found under trees, light that is not absorbed by the leaves is more able to reach the mushrooms. There is another factor influencing the light: shorter wavelengths are more efficiently scattered, so the blue light is scattered and re-scattered and moves easily through the leaves[6]. Plants and fungi absorb mainly the blue-light spectrum because it provides a greater source of photon energy, independently of the purpose.

In mushroom physiology, light is a generally unexpected requirement. Based on *Agaricus* cultivation in the dark and on traditional compost, there are many jokes about feeling that others must think one is a mushroom because he is kept in the dark and fed undesirable things. Yet, wild *Agaricus* is found in grassland with a good supply of sunlight and all cultivated mushroom species that are native to forest floors with very little light, require light. At first this seems to be a wasted resource for the mushrooms. However, when we analyze their environment and life cycle more thoroughly, it begins to make sense. The biological purpose of the basidioma is to bear and distribute spores to propagate the species. Forest mushroom species generally grow from dead wood. If that wood is laying just above the forest floor and the mushroom sprouts from the bottom of the wood, it might continue to grow down towards the earth and thereby reduce its ability to distribute the spores. While *Agaricus* and other grassland species would seem to have light, in their natural environment that they could use, they sprout from the surface of the soil and the only direction available is upward.

Clearly the sun can be used for the needed light, but it brings unwanted heat. For a number of years, fluorescent lights specifically intended for supplying light for photosynthesis have been available. More recently LED lights have been produced for that purpose. Since mushrooms appear to require a very narrow waveband with very little intensity, a well designed LED light might be of special value for growing. There are several things to consider, both positive and negative. First, lights producing a narrow waveband will be worthless for picking and other human activities. However, light needed for human activities will not be required over as many hours, as the mushrooms seem to require light. Installation of two lighting systems will be an extra bother, but electric power cost and longevity of the lights should save considerable money. LEDs also generate less heat and may save on cooling costs.

Most of us are accustomed to small LEDs that produce no noticeable heat and we have been told that LEDs are extremely efficient. The facts are quite different (**Table 1**). It is true that fluorescent lights are much more efficient than incandescent lights, but LEDs are only somewhat more efficient than fluorescent lights. However, we have found no light with a label that suggests it is as much as 50% efficient. Brand, Wattage and color (Kº) all influence efficiency. So the future may bring much more efficient LEDs. Brand seems to have little effect on the efficiency of incandescent and fluorescent lights. In general, for every type of light, greater Wattage is more efficient in converting electricity to light. It would also seem that our adoption of 200 lumens per Watt as 100% efficient grants all electric lights greater efficiency than fact. If we decided that 60% of visible light (**Fig. 6**), must be used for efficiency calculations,

Table 1. The efficiency of several electric lights, based on Watts of electricity in and Watts of light put out. Lumens, K, and Input Watts are manufacturer's data.

Type	Brand	K	Input Watts	Lumens Total	Lumens per Watt	Lumens % Efficiency*
LED	Philips	3000	10.5	800	76.2	38.1
LED	Cree	2700	9.5	800	84.2	42.1
LED	Cree	5000	9	800	88.9	44.5
LED	Cree	2700	6	450	75	37.5
Fluorescent	Ecosmart	2700	14	850	60.7	30.4
Fluorescent	Ecosmart	5000	14	800	57.1	26.6
Incandescent	GE	2700	60	800	13.3	6.7

* Basis: Fig. 6, Lumens per Watt at 50% of the width of the curve (200 Lumens equals 100% efficiency).

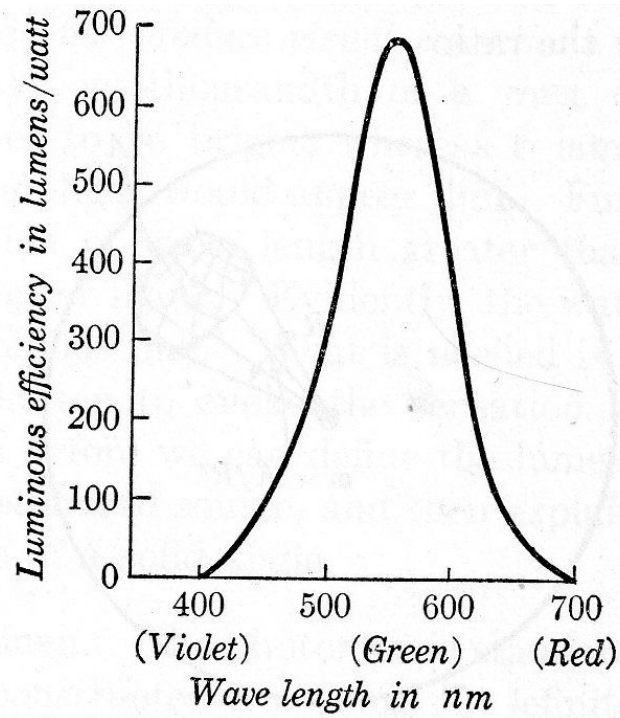

Fig. 6. Lumens per Watt for one nanometer wave length increments of visible light[21]. It is important to notice that lumens and lux are based on normal human acuity and are unrelated to other biological activity.

100% would become 300 lumens per Watt and all percent efficiencies would be reduced by one third.

ULTRAVIOLET LIGHT

Olaizola *et al.* presented a view of what fungi can do to protect us from the harmful effects of ultraviolet light[20]. It seems appropriate to assume that, as they suggested, fungal melanins may be important to the survival of spores, especially of species that grow in meadows or open sunlight.

Another important function of ultraviolet light is turning ergosterol into vitamin D_2. For many years ultraviolet irradiated ergosterol has been added to milk with the idea of eliminating rickets in children and with considerable success. Of course, it was added only to processed milk in industrialized countries. However, the ultraviolet from the sun on bare skin also can do the conversion and also can convert animal sterols to vitamin D_3. The two forms of vitamin D are essentially equal in humans. Yet, there are several groups of people who often do not get an adequate supply of vitamin D. One is post-menopausal women, they have a high requirement. Many of those women eat little with preformed vitamin D and often do not spend much time in the sun exposing much bare skin. Another group is people with dark skin. That color is melanin and has the same effect as the fungal melanin that Olaizola *et al.* described[20]. It has been stated that, "UV transmission of black skin is considerably less than that of white skin. At 300 nm, black skin transmits approximately 2-3%, whereas in white skin 20-30% is transmitted[10]." A 10x difference is not easily compensated for.

The effectiveness of the melanin was measured by the protection it afforded to human cells. Ultraviolet light is often used to reduce microbial contamination, especially air borne cells in rooms. It has two weaknesses for that purpose, it does not kill quickly and generally there will be places that are shaded from the ultraviolet light, as melanin does for human cells. So, it will reduce viable cells, it will not sterilize the air.

The optimum wavelengths for the conversion of ergosterol to vitamin D_2 is apparently 275 to 300 nm[14]. Early work was done by irradiating purified ergosterol and somewhat later it was noted that the conversion occurred within the human body exposed to the sun. Apparently, it was not until 1974 that whole mushrooms were irradiated. They were shown to contain 400 IU vitamin D_2 per gram, derived from natural ergosterol[19]. While other fungi produce ergosterol and people eat several, including blue cheese made with *Penicillium*, bread and other food made with yeast, but only mushrooms are almost universally eaten as discrete units.

It is hoped that we can learn if ultraviolet irradiated mushrooms might be an especially desirable food for post-menopausal women and for all people with dark skin, especially those who do not live in sunny climates.

Mercury vapor lamps with quartz tubes are often used to reduce microorganism in the air. They kill microorganisms in the same way that sunlight kills human skin cells[17]. The lamps work, but require time, can not reach around objects and like all lights are attenuated by the square of the distance from the lamp. So one lamp will be effective in a very small area with no objects and no air movement. Since they kill microorganisms, they also kill skin and eye cells.

CONCLUSION

Many characters of light have been discussed, there are reasons for applied mycology to be interested in all three spectral ranges of light. Infrared can supply information on many parameters that are important. Visible light is required by almost every human, but most mushrooms require one rather narrow bands of visible light and the nutritional value of edible fungi can be improved by another narrow band. The approximately 460 to 480 nm of blue light that is important to the production of the basidoma of most cultivated mushrooms and approximately 275 to 300 nm will convert the ergosterol in the mushrooms to vitamin D_2. While current prices of LED lamps are high compared to fluorescent and incandescent lamps, their typical longevity and low power consumption makes them of interest. The low power consumption is particularly appealing, if the lamps are made specifically for the narrow bands we require, then we would expect that little energy would be wasted on light that was not accomplishing our needs. The author (RK) has been in contact with a producer that has the capability of producing LED lamps of narrow bandwidths. The thought is that these might be produced so that they could run on 12 volt solar panels with batteries. The ultraviolet unit might be small and able to be transported between several farms.

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