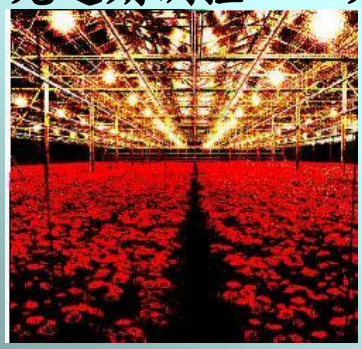
甚麼是光?

可以產生視覺效果的電磁波能量

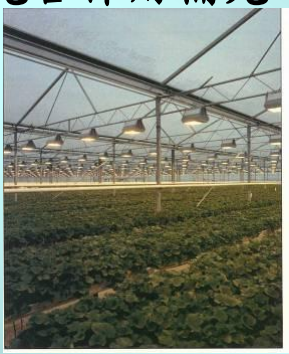
光的不同應用

光週期調控



photoperiodism

光合作用補光



photosynthesis

光質影響

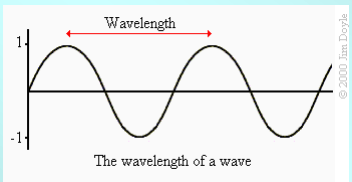
photomorphogenesis

與栽培作物相關的光的特質

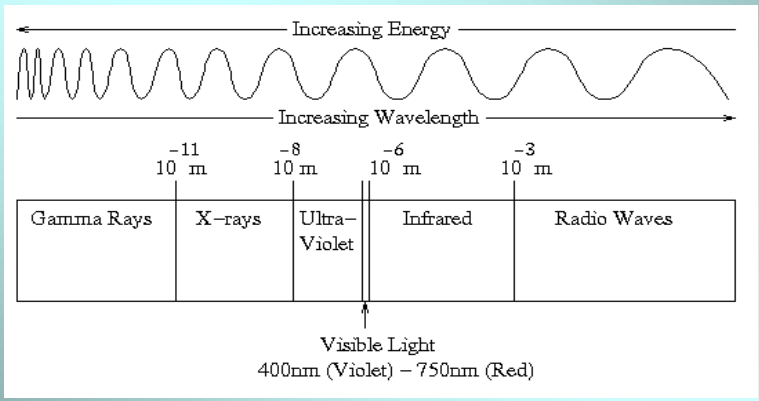
- 光量(強度)
  - 光合作用
- 光質(波長-顏色)
  - 光型態發生
- **累計時間**
  - 光週期

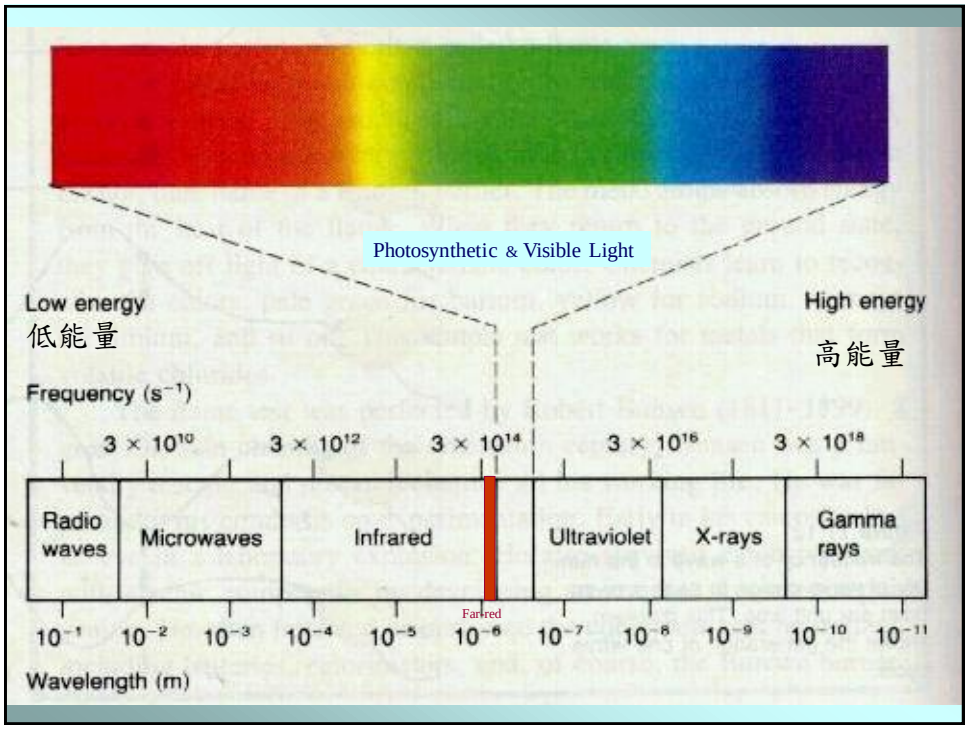
光的兩種說法

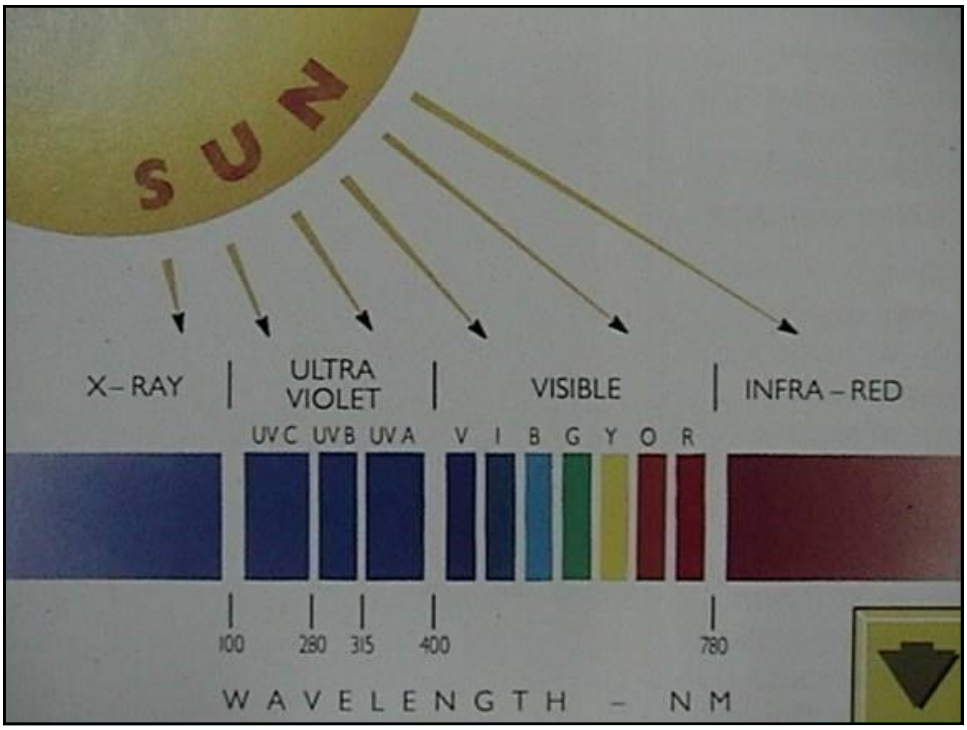
- 顆粒
  - 光的行為就像一堆有能量的粒子
  - 光子 (光量子)
    - 對作物非常重要
- 波
  - 電磁波可有很短或很長的波長
  - 能量與波長成反比
  - 短波長代表高能量



能量與波長(λ)的關係


Increasing Energy
Increasing Wavelength
10^{-11} m
10^{-8} m
10^{-6} m
10^{-3} m
Gamma Rays
X–rays
Ultra–Violet
Infrared
Radio Waves
Visible Light
400nm (Violet) – 750nm (Red)


Photosynthetic & Visible Light
Low energy
低能量
High energy
高能量
Frequency (s^{-1})
3×10^{10}
3×10^{12}
3×10^{14}
3×10^{16}
3×10^{18}
Radio waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma rays
Far red
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Wavelength (m)



電磁波如何產生

任何物體溫度在絕對零度以上都會輻射電磁波

- 輻射的電磁波能量取決於物體的溫度
- 提高物體溫度等於提高總輻射出去的能量
- 史蒂芬-波茲曼 Stephan-Boltzman 定律

溫度 vs. 波長 (λ)

- 溫度與輻射出去的電磁波波長成反比
- 煒恩定律：由物體輻射出去的電磁波波峰位置的波長與絕對溫度成反比 (λ=2897/T, λ in um, T in K)
- 可以透過控制物體的溫度來控制光的顏色

色素與光吸收

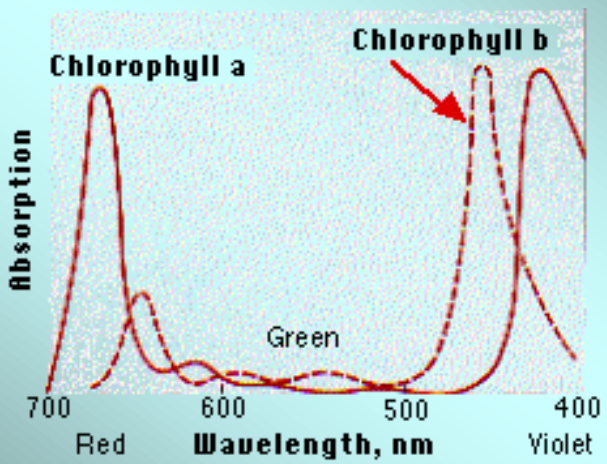
吸收特定波長的物體

色素 是 物體內的一種化學物質 可接受特定波長使得該物體具有某種特性。

COLOR

光的受體

葉綠素 chlorophylla a, b 的吸收峰
位於紅光 600~700 nm 與藍光 400~500 nm 波段



植物體內的色素

Pigment	Light Absorbed	Light Reflected
Chlorophyll 葉綠素	violet, blue, red	
Carotenoids 類胡蘿蔔素	blue	Yellow Orange
Zanthophyll 葉黃素	blue	Yellow Orange
Melanin 黑色素	most visible light	Black
Anthocyanins	blue, UV	Red
Phenolics	UV	

光量量測：光感測器

Solar Radiation Sensor

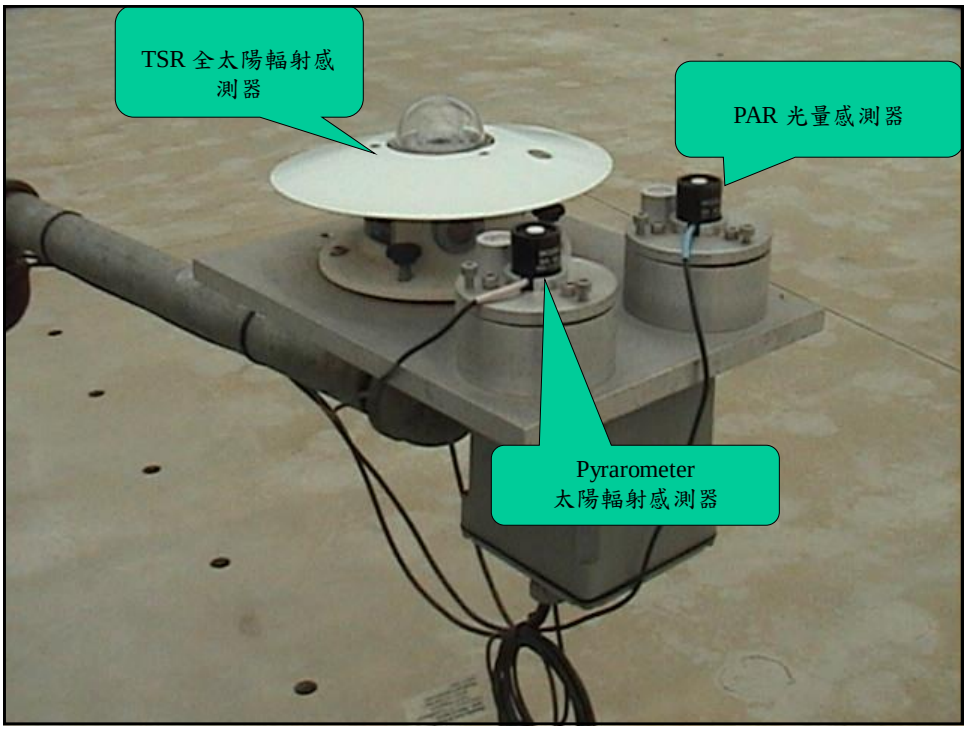
ES Radiation sensor is a quantum sensor that is enclosed with 4-20mA adapter. The sensor may be purchased as part of a Meteorological station or as stand-alone sensor. As a quantum sensor it is designed to read velocities of radiation in the viewable spectrum; 400-700nm, which is the Photosynthetically-active radiation (mostly known as PAR). The 4-20mA adaptor is factory set to give a read of 4mA when there is no sense of radiation in the spectrum, and 20mA (full scale) at 2000 PAR. It needs DC power supply of 26-13V for its basic functionality.

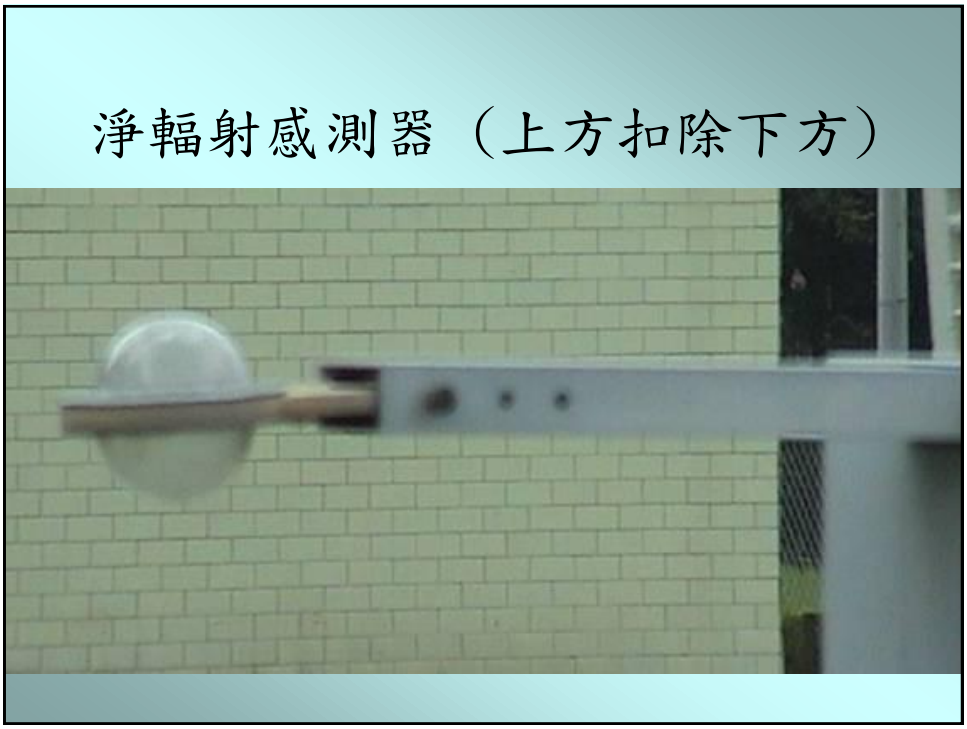
Photometer 照度	Illumination, in *Lux*

Quantum Sensor 光量	Photosynthesis, in μmol/m^2/s

Pyranometer 輻射能	Solar energy, in W/m^2

四種光感測器安裝於於溫室內

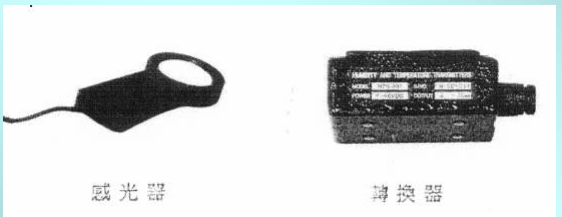

TSR 全太陽輻射感測器
PAR 光量感測器
Pyrarometer
太陽輻射感測器


淨輻射感測器（上方扣除下方）

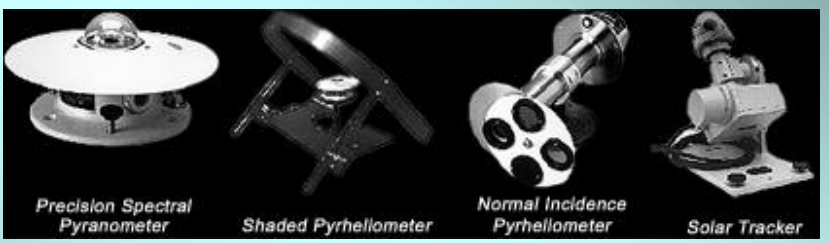
光感測器

- 全太陽輻射光譜，單位：W/m^2
- PAR (Photosynthetically Active Radiation)：光合作用有效光，400~700 nm 範圍內的光子數量，單位： $umol/m^2/s$
- 輻射感測器，單位：W/m^2
- 所有光量感測器都必須水平擺放，一般會安置於可調整水平的座台上

照度計



其他太陽能相關感測器



可攜式

三種不同量測單位

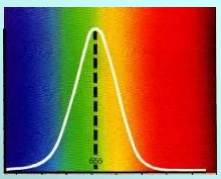
LI-190: Quantum

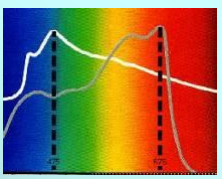
LI-200: Pyranometer

LI-210: Photometric meter

人眼與植物的敏感度曲線及太陽光譜

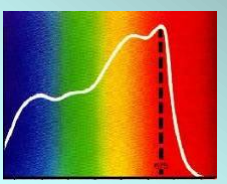
Human





Spectral irradiation vs. sensitivity curve of Plants

Plant



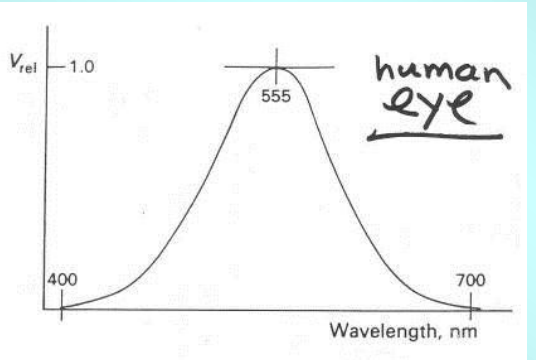
量測照度

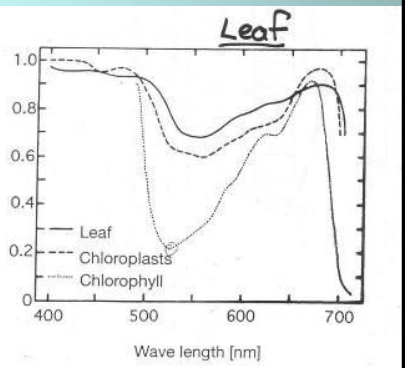
- 以人眼對光線的敏感度為依據
- 非常主觀
- 常用單位 = 1 呎燭光foot candle (ftc), lux

  • ftc or fc:距離1 根蠟燭1英呎量到的照度

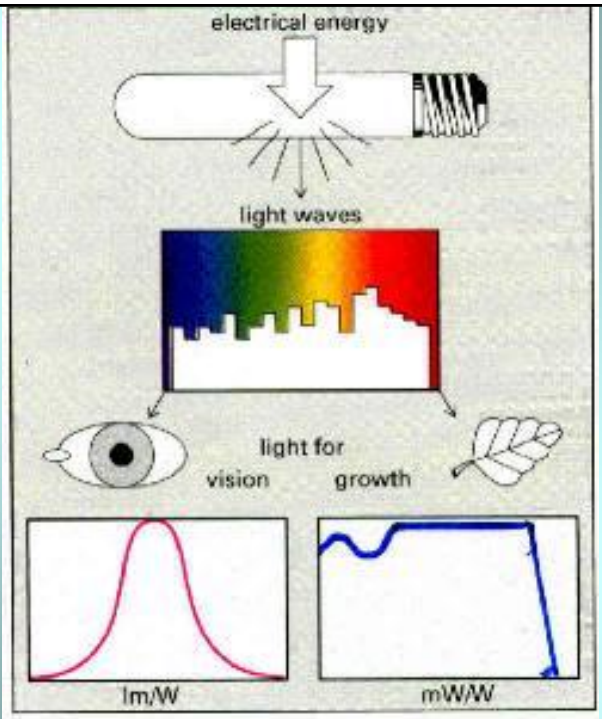
  •Lux:距離1 根蠟燭1 m量到的照度

光的敏感度曲線
人眼 vs. 葉片





人眼與植物感受到的光相差頗遠



園藝業界改不過來的陋習

- 仍然使用Lux 或 fc 的照度單位
- 此單位只對空間照明有意義
- 涉及人類眼睛內的錐狀體與柱狀體對光線的敏感度
- 由於植物感光機制與人眼不同，不宜使用此單位，但已積習難改
- 此類感測器稱為photometric sensor

量測輻射能

- 以能量的觀點量測電磁輻射
- 使用單位= W/m^2
- 缺點
  - 與波長不相關

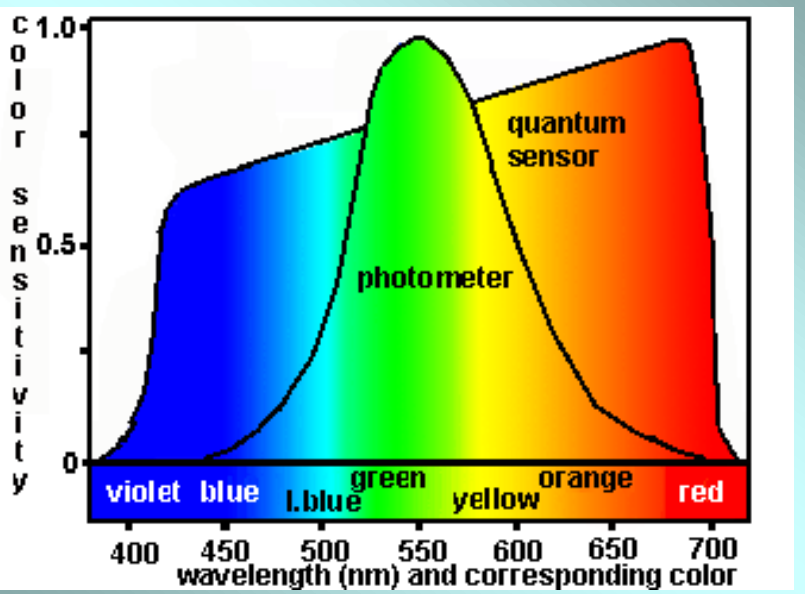
量測光量子

- 只量測與光合作用直接相關的波段，以光合作用有效光Photosynthetic Photon Flux (PPF)稱之
- 波段範圍侷限於400-700 nm
- 使用單位： $\mu mol/m^2/s$

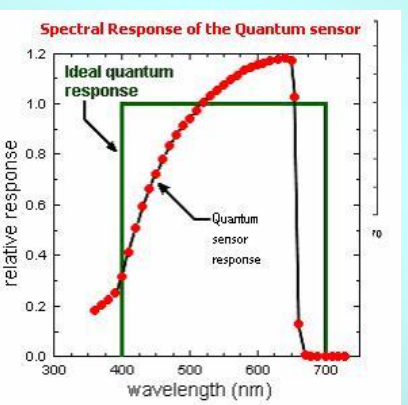
  其中 = mol = (6.02×10^{23}) photons

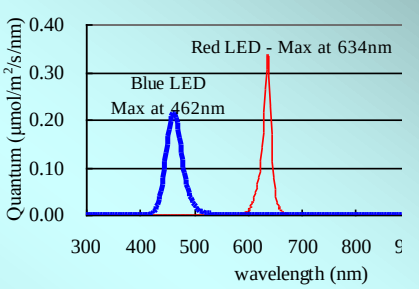
  = μmol = (6.02×10^{17}) photons

感測器的敏感度曲線



光量子感測器的限制





Quantum Sensor
can not be used to
measure red or blue LEDs

光量（光的強度）

直接影響：

1. 光合作用
   - 直接與接受到的光子數量有關

$CO_2 + H_2O + \text{Light Energy} \rightarrow (CH_2O)_n + O_2$

2.植株高度

3.植株分化 (開花)

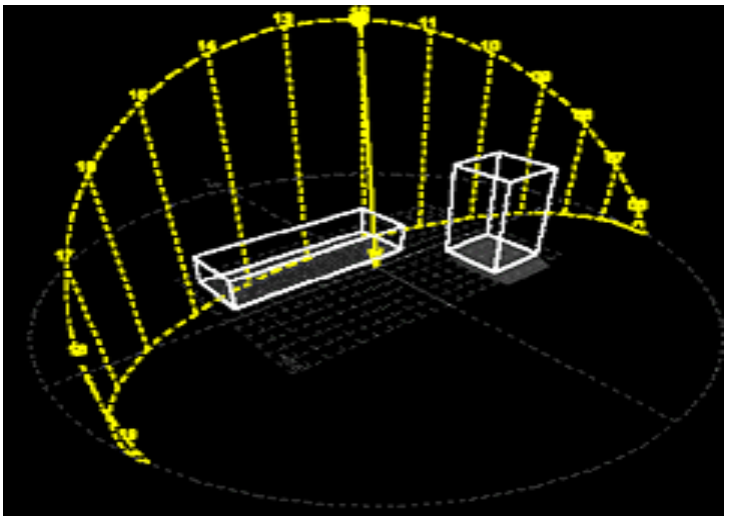
可用光的限制因子

- 季節
- 緯度
- 一天中的時間

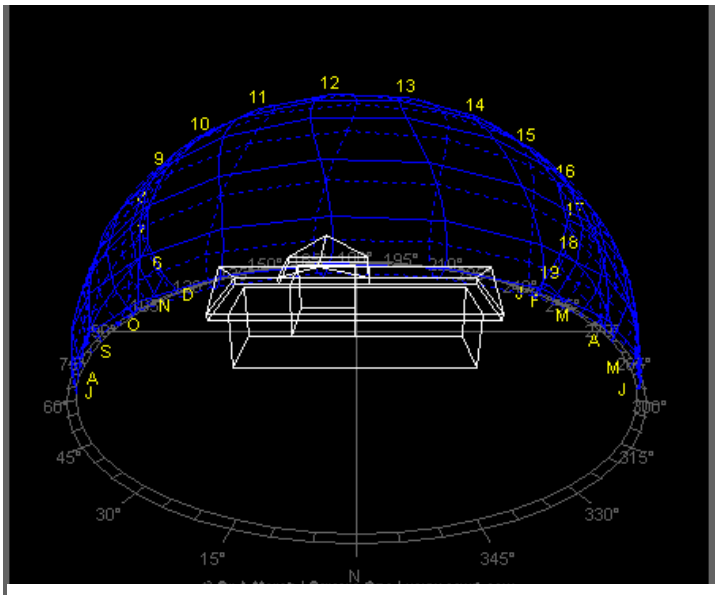
影響太陽的角度

- 雲層、設施被覆資材

一天中太陽的軌跡



3 D View

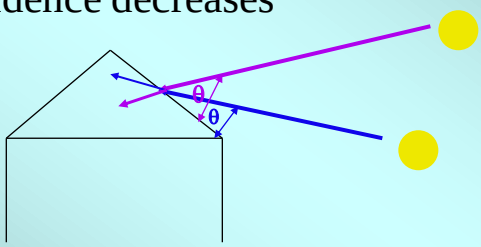


Southern Lat. 32 deg.

光線的入射角與強度

Lambert's cosine Law

As you change the angle of incidence (θ), the intensity of a light beam will decrease as the angle of incidence decreases



The reduction carries over into the amount of light that passes through the greenhouse covering.

入射角

90^{o} is the angle at which transmission intensity occurs

As the angle of the sun hitting the greenhouse roof increases to 90^{o}, light transmission into the greenhouse increases.

In general, the higher the sun is in the sky, the greater the transmission into the greenhouse.

Low sun angle in the winter along with short days dramatically reduce light levels in the greenhouse during that time of the year.

Time of Year

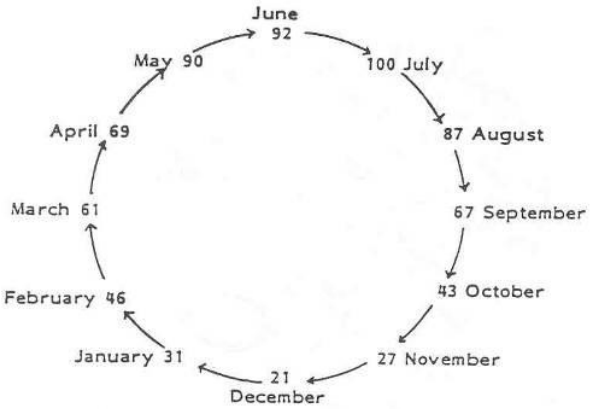
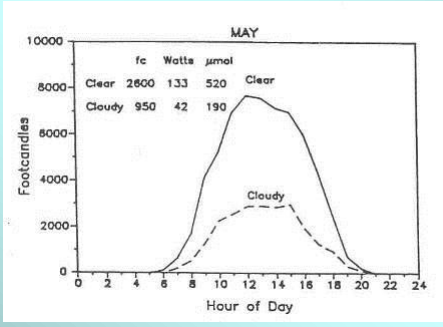
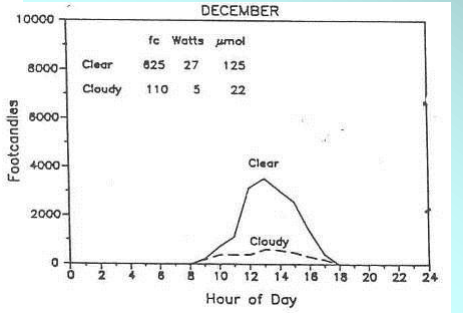
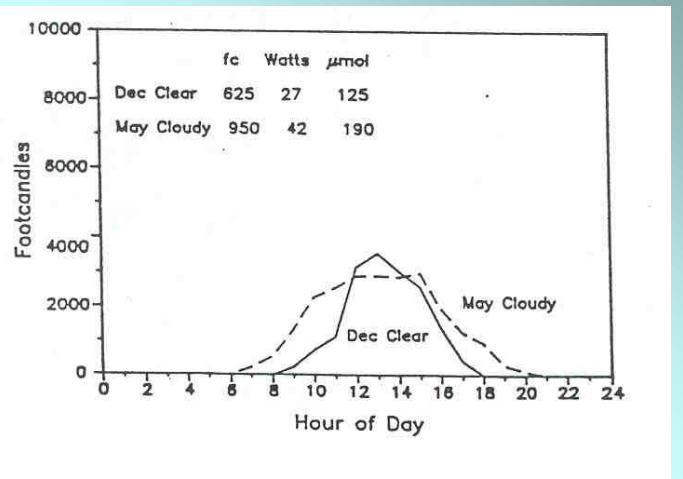


Figure 1. Monthly solar radiation level as percent of maximum month (July). Average of langley's of radiation recorded by the U.S. Weather Bureau at Madison, WI, for a five-year period

Cloud Cover







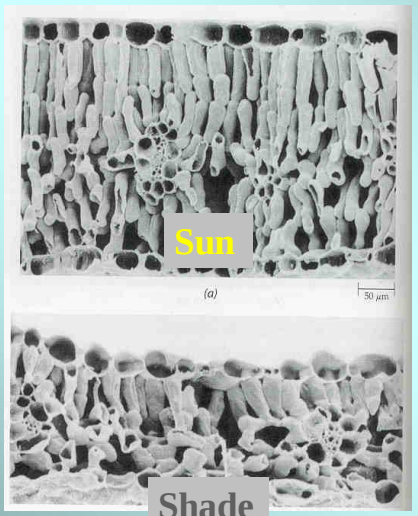
五月的陰天可比十二月的晴天提供更多的光量是由於光期時間的拉長

低光狀態下的植物生理

1. 較長的節間距離，使莖拉長
2. 較大的葉表面積
3. 較薄的葉片與莖
4. 較薄的角質層
5. 一層柵狀細胞

為了最大化光合作用所做的調整

Sun vs. Shade Leaf



猜猜哪一株沒見過光線

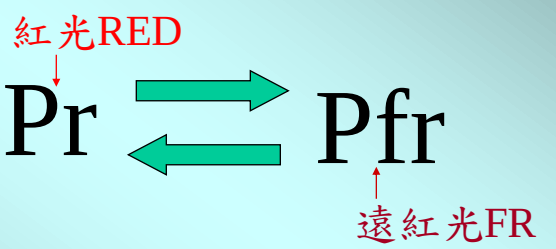
兩株百合都開花了

但高度相差這麼多

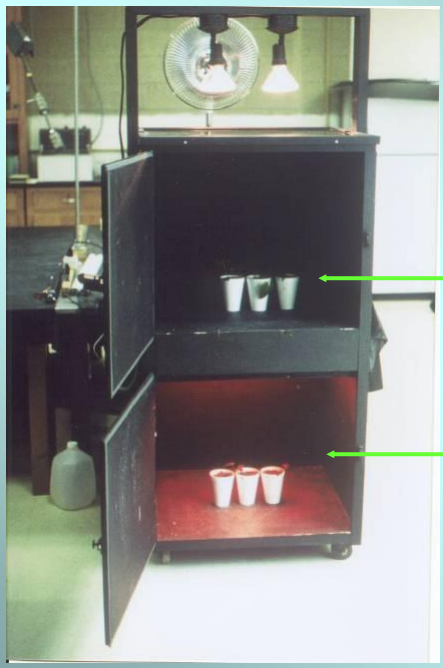
光質

- Controls Photomorphogenesis (plant development and form)
- Mediated by phytochrome (protein pigment)
  - red light absorbing form (Pr)
  - FR light absorbing form (Pfr)
  - Forms are photoinconvertible, depending on the which type of light is absorbed

光質



- 兩者均影響植物
- 最終的影響就看是何者主控



人眼看不到FR

此FR盒有5倍於R 盒的能量

植物對較低的 R:FR值 (通常 < 1)的反應

Low R:FR can result from increase in FR or reduction in Red and is indicated by:

1. Elongated internodes (stretching)
2. Reduced lateral branching
3. Elongated petioles
4. Larger, thinner leaf blades
5. Smaller total leaf area (due to lower numbers of leaves
6. Reduced chlorophyll synthesis

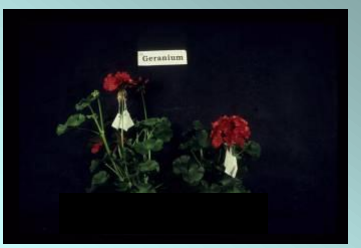
植物對較高的 R:FR值 (通常 > 1)的反應

較高的 R:FR 值可能是減少紅外光(FR) 或是增加紅光(R)

1. 節間縮短
2. 增加側芽
3. 較小花瓣
4. 較厚較小葉片
5. 較多總葉面積
6. 增加葉綠體數量 (深綠色)

R:FR < 1	R:FR > 1
Elongated internodes (stretching)	Reduced internode length (short stems)
Reduced lateral branching	Increased lateral branching
Elongated petioles	Shorter petioles
Larger, thinner	Thicker, smaller leaves
Smaller total leaf area (due to lower numbers of leaves)	Greater total leaf area
Reduced chlorophyll synthesis	Green (increased chlorophyll)

哪一種比較強健？哪一種較美觀？

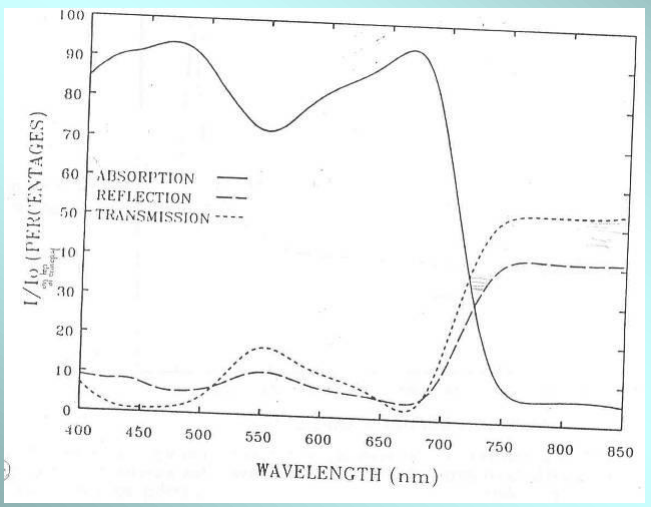


以上圖片中何者是在 R>FR 的情況下栽培的 ？

避遮反應

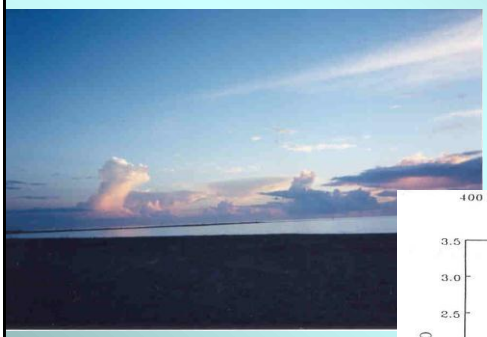
- Leaves strongly absorb red and blue light
- The closer plants are to a neighboring plant:
  - less red light available for absorption
  - still have nearly all FR light present because of FR is transmitted and reflected but not absorbed
- Phytochrome responds to the quality of light within the canopy of crowded plants
- Mechanism by which plants can tell how close neighboring plants are and out-compete for available space
- 在密植狀態下Pr為主控的光敏素，Pr 引起避遮反應

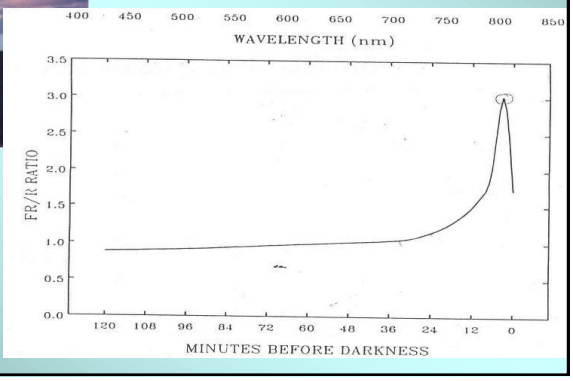
葉片對不同波長的光能的反射、吸收與穿透率



光敏素 Phytochrome 的其他反應

可偵測一日將盡
End of Day Response





偵測一日將盡

- Plant response to the changes in the ratio of Red/FR light
- As day progresses, greater chance of scattering light in atmosphere because of lower sun angle
- Shorter λ have greater probability of scattering

- At end of day, lowest Red/FR ratio for the day
  - red light scattered much more than FR

EOD - important in timing of photoperiodic flowering

光週期
光期長度

As a result of seasonal changes in daylength, plants have evolved systems to ensure viability of seeds:

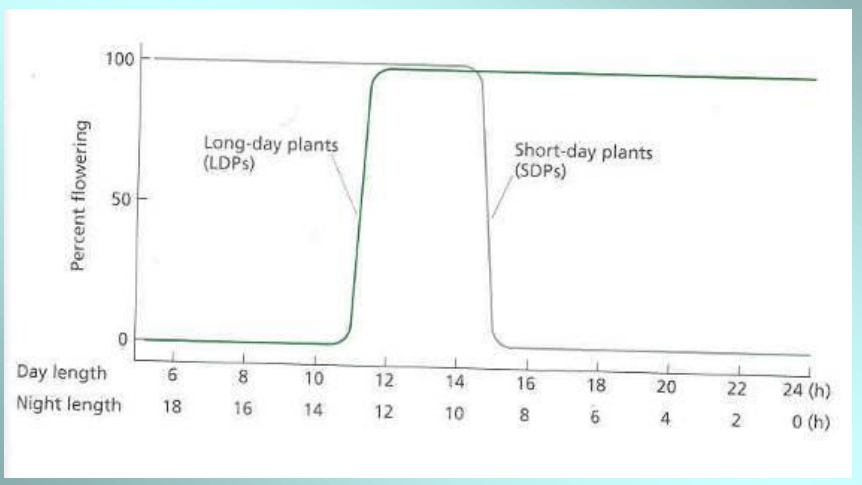
- protection before winter
- coincide with the rainy/ dry seasons

Photoperiodism - plant ability to detect and respond to day length

光週期

- 短日照植物，當日長低於某臨界時數就開花
- 長日照植物，當日長高於某臨界時數就開花
- 日中植物，開花不受日長之影響

光週期



光週期的調節

植物主要是偵測夜間的長度

That means that during short day periods of the year by interrupting or splitting a long night with a relatively short photoperiod the plant perceives a short night and long day effect even though the natural day length has not changed

作物依光週期分類

- Obligate強制的 - plant that must absolutely meet the day length requirement to flower
- Facultative授權的 - plant that will flower under most photoperiods but will flower most readily when the photoperiodic requirement is met

光週期調節的優點

- 允許全年有花
- 在過去
  - 菊花只有秋季銷售
  - 康乃馨只能在春天與早夏生長
  - 蝴蝶蘭只有過農曆年有花

溫度的交感作用

臨界日長通常與溫度有關

- 短日植物(SDP)，當溫度增加，臨界日長縮短
  - Mums菊花
  - Poinsettias聖誕紅
- 長日植物(LDP)，當溫度降低，臨界日長縮短
  - Fuchsia倒吊金鐘
  - Spinach菠菜

溫室內光量調控來控制植物生長

光的特質

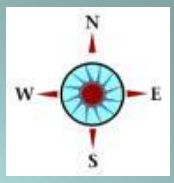
- 光量
  - Photosynthesis
- 光期
  - Photoperiodism
- 光質
  - Photomorphogenesis

光量最大化決定於

- 溫室設計
- 使用被覆資材
- 作物間距
- 其他會吸收/反射光線的物體

Greenhouse Orientation

(direction the ridge runs)



East-West

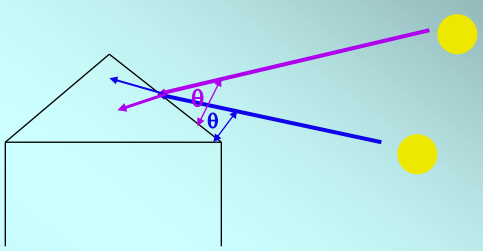
- More light interception
- More permanent shadows
- More snow blown off roof by wind (<40° N or S)

North-South

- Less light interception
- Less permanent shadows
- Better natural ventilation (<40° N or S)

光線的入射角

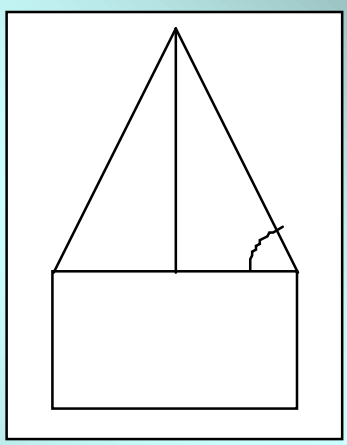
- If light strikes roof at 90˚, then have maximum light transmission
- If light strikes roof not at 90˚, then less light transmitted



緯度越高越需要留意
- 單棟 → 東西向
- 連棟 → 南北向

透過屋頂的坡度來最大化入射的光量

- 高緯度地區譬如美國俄亥俄州 (~40˚N) 的冬季，太陽入射角度很低
- 屋頂需要超過60度，使光線正向屋頂斜面來接受最大光量



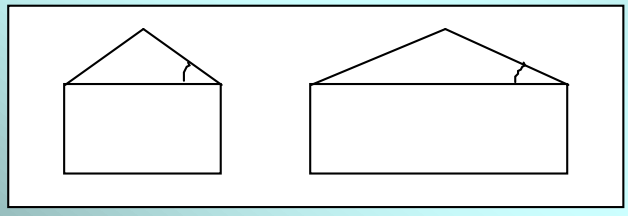
溫室跨距與屋頂斜度

	不同屋頂斜角的屋脊高度	
溫室跨距	**屋脊高度 @ 26˚斜度**	**屋脊高度 @ 63˚斜度**
21 ft (6.4 m)	5.1 ft (1.53 m)	20.6 ft (6.18 m)
32 ft (9.6 m)	7.8 ft	31.4 ft
49 ft (14.7 m)	11.9 ft	48.1 ft!

常見屋頂斜角

寬度 < 25 ft　　寬度 > 25 ft (7.6 m)

32˚　　26 ˚



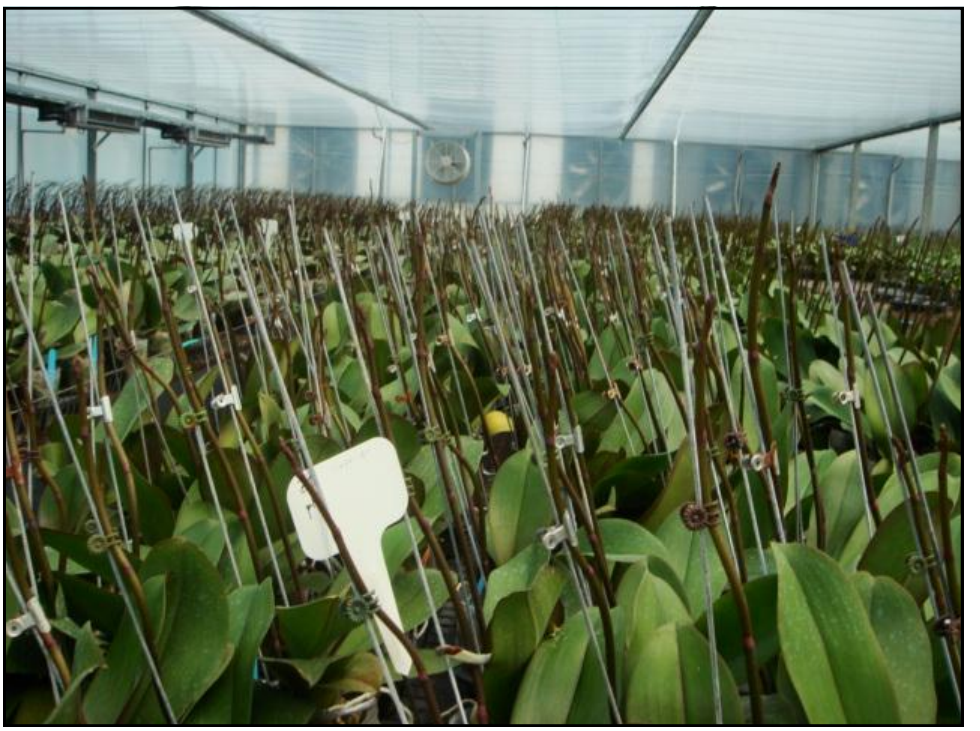
光線穿透率受溫室被覆資材影響也受維護狀況影響

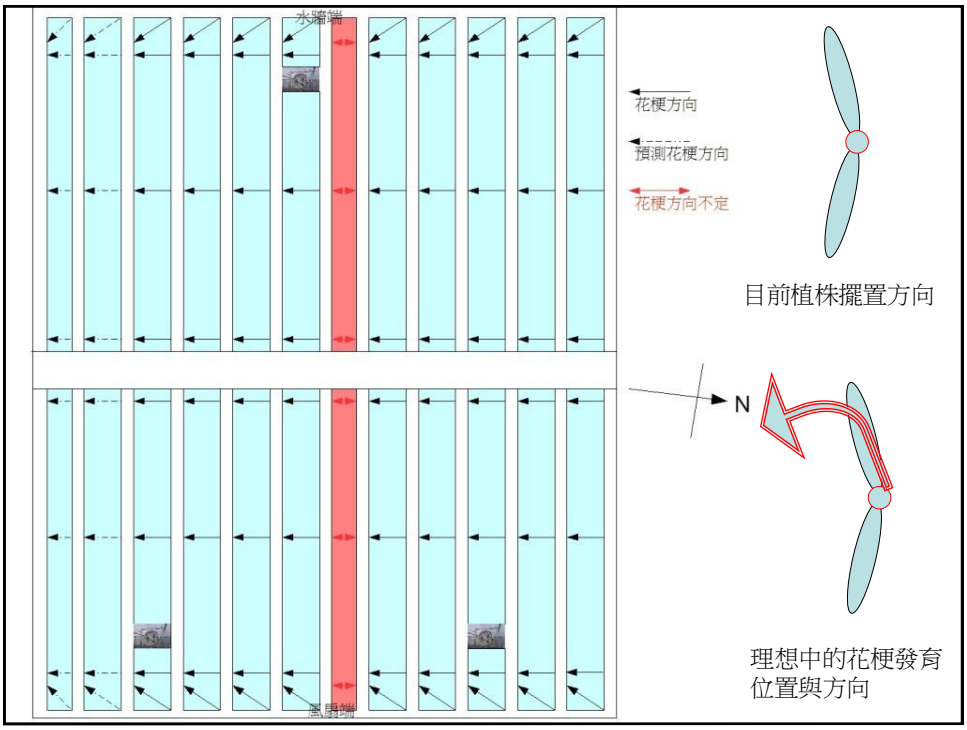
- Glazing Material (% light transmission)
  - Glass (low iron) (93%)
  - Exolite (double acrylic) (92%)
  - Lexan (double polycarbonate) = (78%)
- Cleaning glazing material
  - Several times a year (usually rainfall will do this)
  - Remove shading compound by mid-October

光線穿透率受溫室結構影響也受維護狀況影響

- Superstructure
  - ↑ superstructure, ↑ shading
  - Heavy glazing requires more superstructure
  - Frame 10-12%, sash bars 5-7% reductions
  - Supplemental lighting fixtures can shade
- Superstructure clean and painted
  - Aluminum = reflective
  - Wood - painted white and kept clean

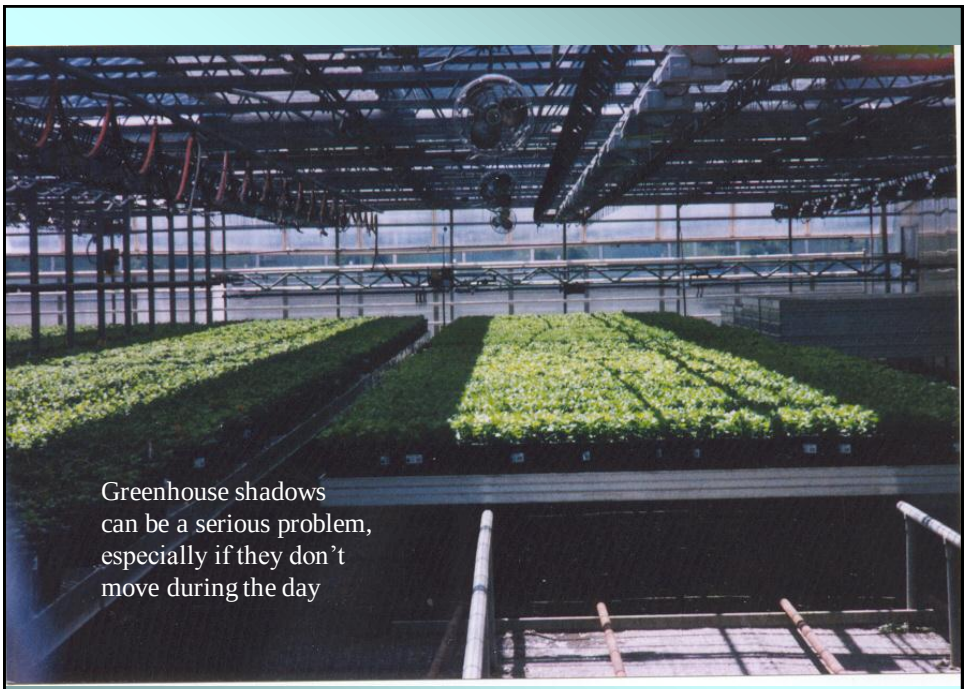
有許多結構會擋光，但還好有塗成白色，所以光線反射效果佳





移走會遮蔭的物體

- Adequate plant spacing
  - Reduces shade avoidance response
  - Don't overdo with the numbers of hanging baskets
- Objects close to greenhouse (trees, buildings, etc)
  - Distance away = 2 x Height of object



Reducing Light Intensity

- Why shade?
  - Low light plants don't like high light
  - Reduce temperature
  - Have reached light saturation point
- Shading methods
  - Shade cloth
  - Shading compounds

Internal and external shade systems

光控

	遮蔭%	透光%
外網1	48	52
外網2	53	47
披覆	68	32
內保溫	25	75

設定目標: 200

氣象站	內保溫開著 室內照度計算值				內保溫關著 室內照度計算值			
照度感測	全開	外網1關	外網2關	全關	全開	外網1關	外網2關	全關
100	32	17	15	8	24	12	11	6
200	64	33	30	16	48	25	23	12
300	96	50	45	23	72	37	34	18
400	128	67	60	31	96	50	45	23
500	160	83	75	39	120	62	56	29
600	192	100	90	47	144	75	68	35
700	224	116	105	55	168	87	79	41
800	256	133	120	63	192	100	90	47
900	288	150	135	70	216	112	102	53
1000	320	166	150	78	240	125	113	59
1100	352	183	165	86	264	137	124	65
1200	384	200	180	94	288	150	135	70
1300	416	216	196	102	312	162	147	76
1400	448	233	211	109	336	175	158	82
1500	480	250	226	117	360	187	169	88
1600	512	266	241	125	384	200	180	94
1700	544	283	256	133	408	212	192	100
1800	576	300	271	141	432	225	203	106
1900	608	316	286	149	456	237	214	111
2000	640	333	301	156	480	250	226	117
2100	672	349	316	164	504	262	237	123
2200	704	366	331	172	528	275	248	129
2300	736	383	346	180	552	287	259	135
2400	768	399	361	188	576	300	271	141

遮蔭網設定

晨間溫度較低允許較高光量

遮蔭

	時段1	時段2	時段3	時段4	
關閉遮蔭網以達成低於	450	330	380	2000	umol/m2/sec
僅當 打開遮蔭網時必需等待	6	分	的低日照		
僅當 關閉遮蔭網時必需等待	1	分	的強日照		

日照震盪

保持遮蔭網 1 關著當 時段1☐ 時段2☐

保持遮蔭網 2 關著當 時段1☐ 時段2☐

保持內溫室 關著當 時段1☐ 時段2☐

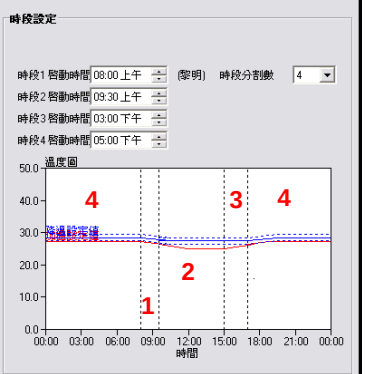
打開遮蔭網/內溫室一小縫 20 %

打開外遮蔭網若風速大於 50 公里小時

關閉內溫室當溫度低於 25.5 °C

關閉遮蔭網以 輔助降溫 ☐

不要打開遮蔭網防 雷雨或下雨中而且日照大於 800 um



光控

	A	B	C	D	E	F	G	H	I	J
1					遮蔭%	透光%			設定目標	
2				外網1	48	52			260	
3				外網2	53	47				
4				披覆	68	32				
5				內保溫	25	75				
6										
7			內保溫開著				內保溫關著			
8		氣象站	室內照度計算值				室內照度計算值			
9		照度感測	全開	外網1關	外網2關	全關	全開	外網1關	外網2關	全關
10		100	32	17	15	8	24	12	11	6
11		200	64	33	30	16	48	25	23	12
12		300	96	50	45	23	72	37	34	18
13		400	128	67	60	31	96	50	45	23
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32		2300	736	383	346	180	552	287	259	135
33		2400	768	399	361	188	576	300	271	141

光控設備 – 白漆

光控設備 –內遮蔭網

光控設備 – 外遮蔭網

	Shade cloth	Shading compounds
Advantages:	Easily applied or removed Known %	Reduces air temps more effectively
Disadvantages:	Not as effective at reducing air temps	More or less permanent (difficult to remove) Have to use specially formulated compounds for both application and removal. Application not uniform

不同應用下所需的光量

Use	umol/m^2/s
Display	15
Photoperiod	10-12
Survival	100
Maintenance	200
Propagation	80
Photosynthesis for Growth and Development	400-1200*

* Photosynthesis is a reciprocal process. Low intensity can be overcome by longer exposure.

光週期調節

- 控制開花期
- 營養生長 vs. 生殖生長
  - 人為短日
    - 黑布
  - 人為長日
    - 日長延長
    - 夜間打斷

人為短日

- Pull black cloth
  - Opaque material blocks all light
  - SDP induced to flower
  - Reflective to reduce heat delay
  - Can be automated
  - Can 'double' as thermal blanket to hold in heat on cold nights

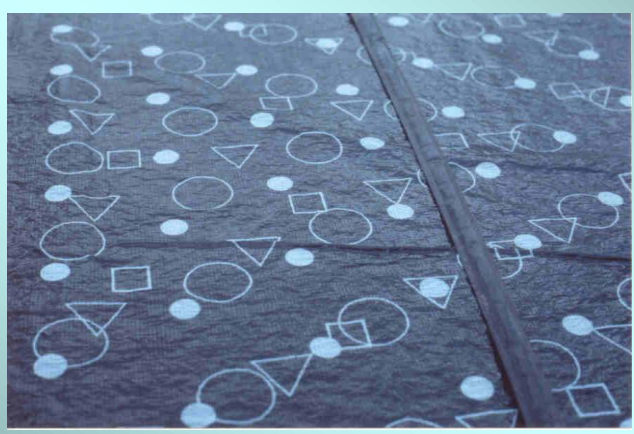
人為長日

- 日長延長
  - 誘導長日植物開花
  - Light (FR containing) for 3-6 hrs at end of day
  - Low intensity (1-3 mmol/m^2/s, 7-10 fc)
- 夜間打斷
  - 防止短日植物開花
  - 2-4 hrs of low light during dark period
  - Want little FR in light

調控 R:FR

- Minimize shade avoidance response
- Remove excess vegetation from plants to prevent self-shading (e.g. geraniums)
- Prevent shading from other plants
  - Minimize # of hanging baskets over plants
  - Proper pot spacing
    - Space visible between plants at least until plants are nearly ready to ship

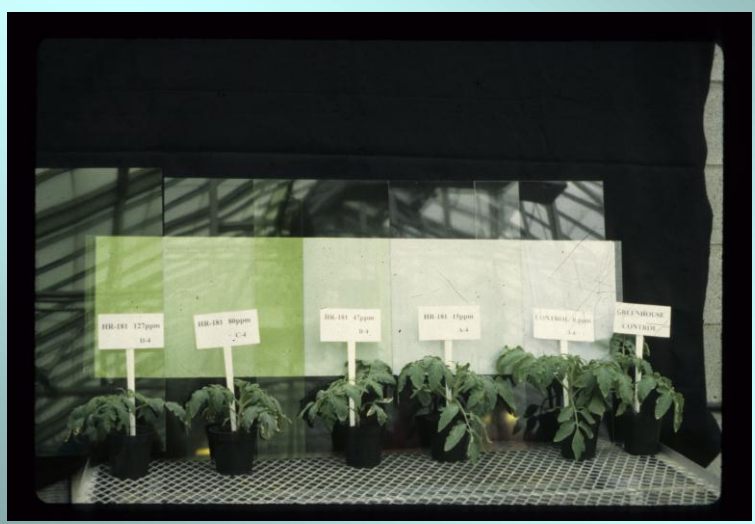
Bench Cover and Pot-spacing Symbols (multi-lingual)



其他作法

- 濾光
  - 塑膠膜添加吸收FR的色素來增加R:FR
  - 技術尚未完全成熟
- 生物科技
  - 更多光敏素讓植物可以看見更多紅光
  - 緊實、墨綠、更多分枝。

顏色愈深的濾紙代表吸收愈多的FR



光合作用人工補光

- 光積值 ＝ 光強度＊累計時間
  - 500 μmol/m^2/s照1小時= 100 μmol/m^2/s照 5小時
- 善用此定律來進行補光設計 (長時間低光量)
  - 透過更多燈具來加強光量會更貴且造成更多遮蔭

日累積光量（光積值）

- 日累積光量 Daily Light Integral (DLI)
- μmol/m^2/s光量子數單位
- μmol/m^2/s x hr/day x 3.6 / 1000 = mol/m^2/day
- 250 x 16 x 3.6 / 1000 = 14.4
- 300 x 16 x 3.6 / 1000 = 17.28 (葉燒發生)

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光量單位轉換

- 以下轉換只適用於太陽光

2000 μE

= 2000 μmol/m^2/s

= 9800 fc 呎燭光 (lumen/ft^2)

= 1060 W/m^2

= 106000 Lux (lumen/m^2)

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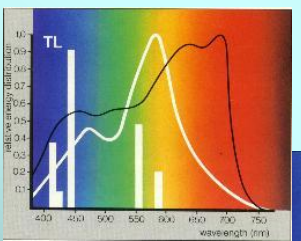
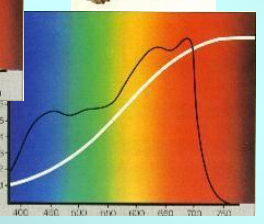
光控設備 – 植物燈

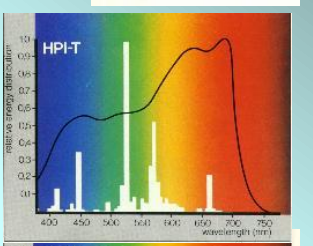
人工光源種類

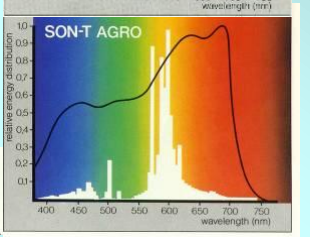
- 燈泡
- 螢光燈管
- 高強度放射燈
  - 金屬燈
  - 水銀燈
  - 低壓鈉燈
  - 高壓鈉燈

太陽之外的光源









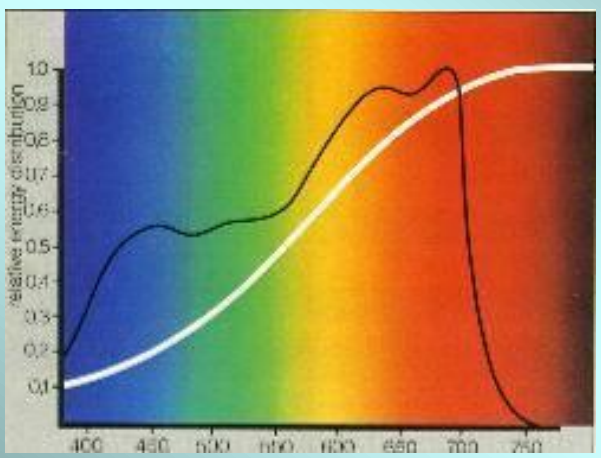
選擇人工光源的考量

- Cost
  - Fixture
  - Installation
  - Energy consumption
- Ease of Installation
- Spectral characteristics (λ)
- Type of crop
- Power (wattage)
- Heat released
- Efficiency
  - Amount of electrical energy converted to light energy
- Life Expectancy
- Output Loss
- Weight of fixture

燈泡

- Easily installed
- Low efficiency
- Low intensity
- Large amount of heat given off
- Spectrum contains far-red (R:FR > 1:1)
- OK for photoperiodic control
  - Daylength extension
  - Night break

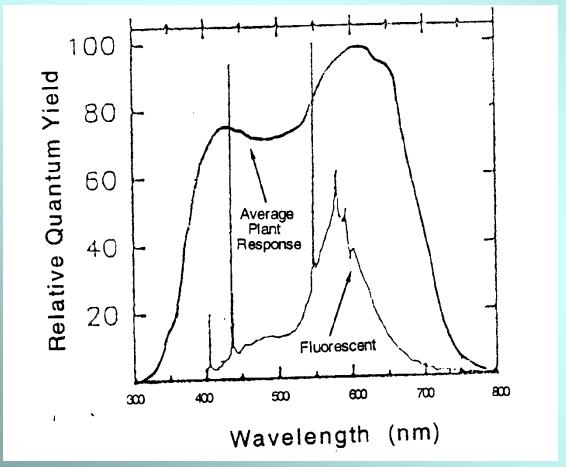
燈泡

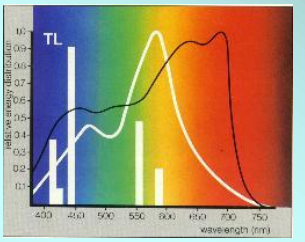


燈管

- More efficient than incandescent
- Low intensity
- Less heat generated than incandescents
- No far-red but some UV
- Good for growth chambers, coolers, and photoperiod (night break) use
- More complicated to install (ballast) than incandescent
- Different phosphors change spectrum

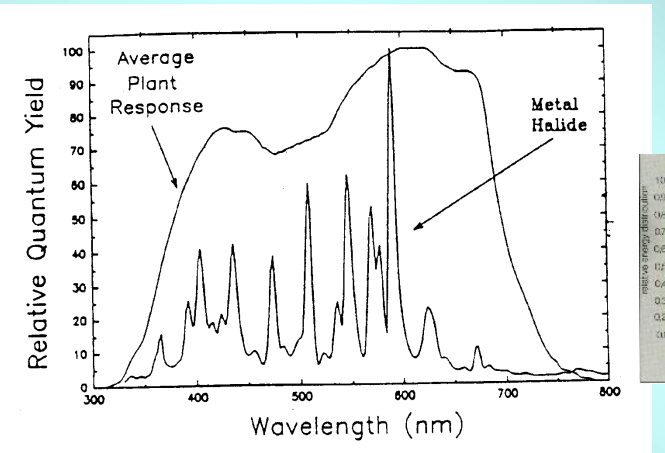
How well does fluorescent spectrum match plant needs?

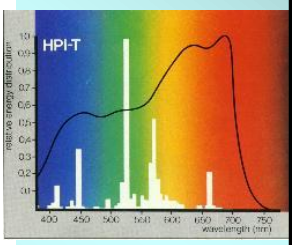




High Intensity Discharge (HID) Metal Halide 金屬燈

光合作用最適合

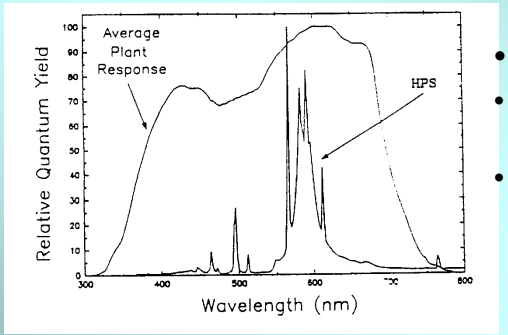




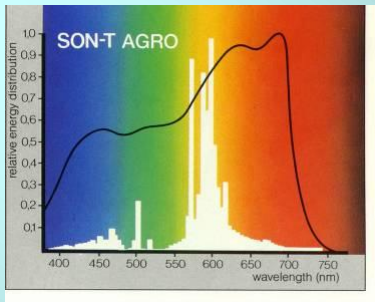
Low-Pressure Sodium (LPS) HID lamps 低壓鈉燈

- 便宜
- 光譜集中於 589 nm附近
- 最不適合植物使用!

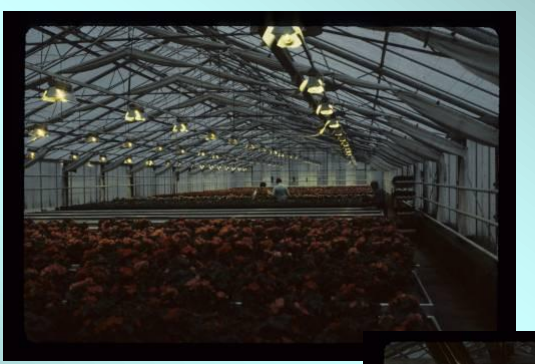
High Pressure Sodium (HPS) 高壓鈉燈



- 在美國溫室頗為普及
- 類似 LPS, 波峰為589 nm但光譜範圍較廣
- 只有一點點的FR

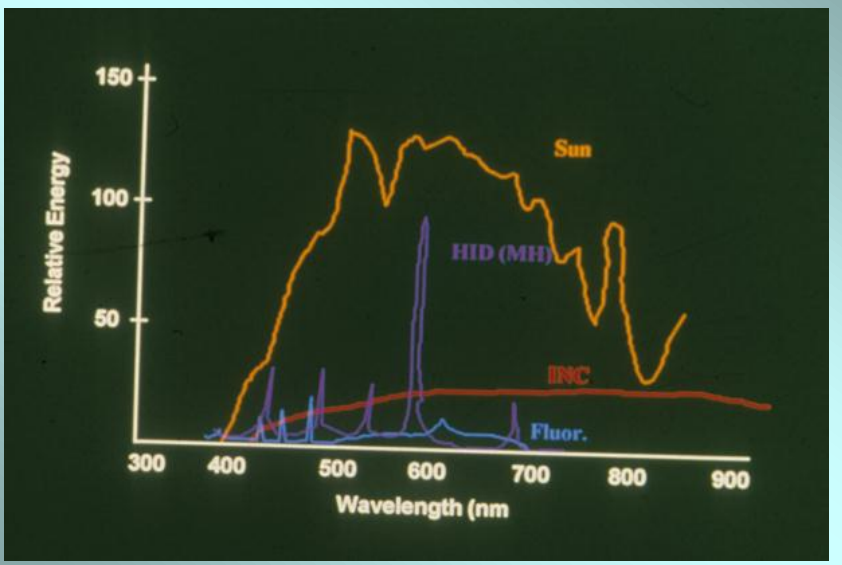


溫室內常見的HID燈具



HID's providing supplemental light for photosynthesis during low light conditions

陽光與三種燈具(金屬燈、燈泡與燈管)的代表光譜



人工光源的選用

- 打斷黑夜

  Fluorescent燈管 > Incandescent燈泡 > HID 高強度放射燈

- 日長延伸

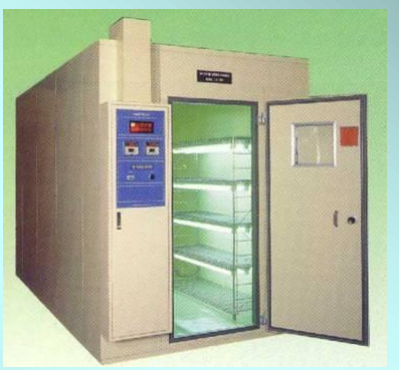
  HID ~~Incandescent~~ ~~Fluorescent~~

- 光合作用光量補強

  HID > Fluorescent* ~~Incandescent~~

  * 最適用於種苗繁殖與冷藏庫

組織培養室/植物生長箱



使用燈管，以冷氣散熱

量產規模組織培養室

使用燈管

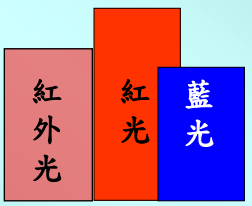
以冷氣散熱

植物工廠內的自走燈具

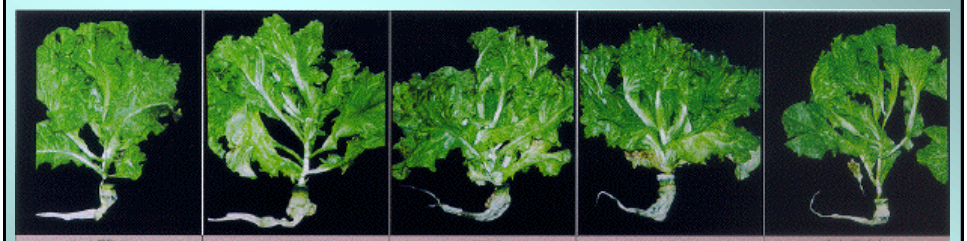
Fang & Jao, 2001

LEDSet: 使用高亮度發光二極體

光量，光質，給光頻率與工作比為可調



應用LED在蔬菜栽培的研究

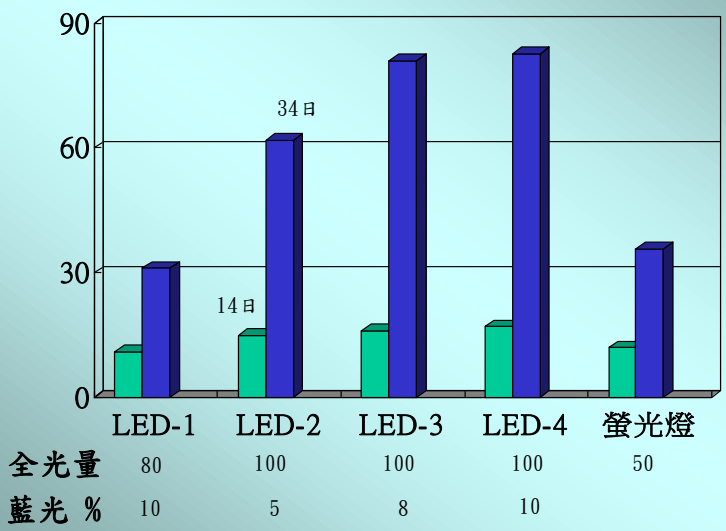


LED-1	LED-2	LED-3	LED-4	白色螢光灯
全光量 80	100	100	100	50
赤色／青色光 72／8	95／5	92／8	90／10	

試験区	LED-1	LED-2	LED-3	LED-4	白色螢光灯
地上部新鮮重（g／株）	31.1 ±6.2	61.8 ±12.5	80.9 ±14.4	82.7 ±16.9	35.7±8.4
地上部乾重 （g／株）	0.9±0.2	1.8 ±0.4	2.4 ±0.4	2.5 ±0.5	1.2±0.3
草丈 （cm）	32±3	29 ±2	25 ±1	24 ±3	30±2
根部乾重 （mg／株）	188±20	244 ±49	298 ±48	342 ±68	211±42

※栽培日数34日、値は22株の平均値±標準偏差。

地上部鮮重

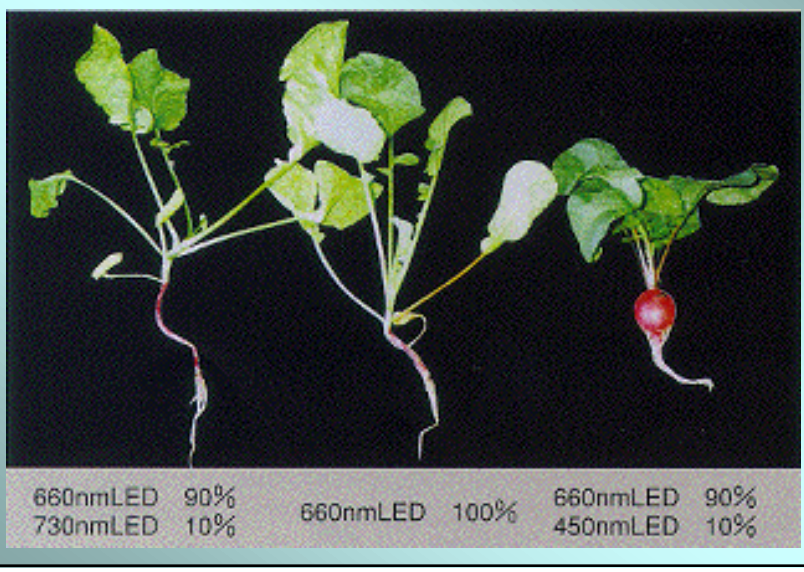


紅藍光比例9:1最佳

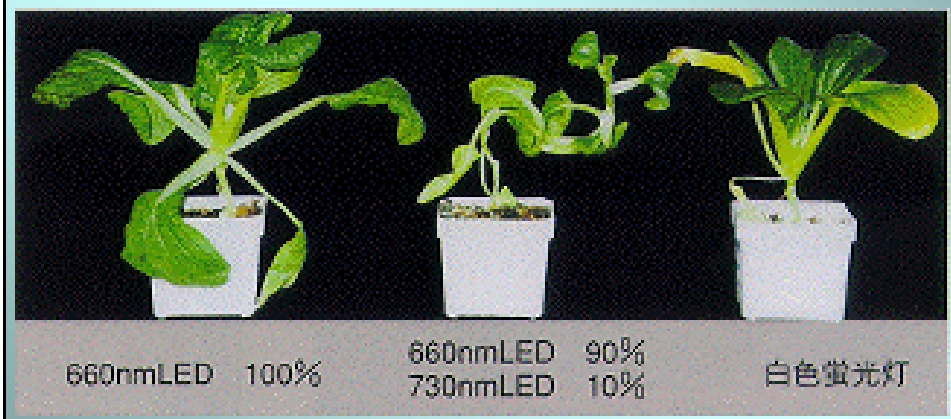
光質影響口感與營養

	紅光 660nm	紅光660nm +紅外光730nm	螢光燈
地上部鮮重 (g/株)	10.3±3.6	6.5±1.8	6.7±2.4
纖維質 (%)	3.8	1.7	2.9
維他命C (mg/100g)	27	72	54

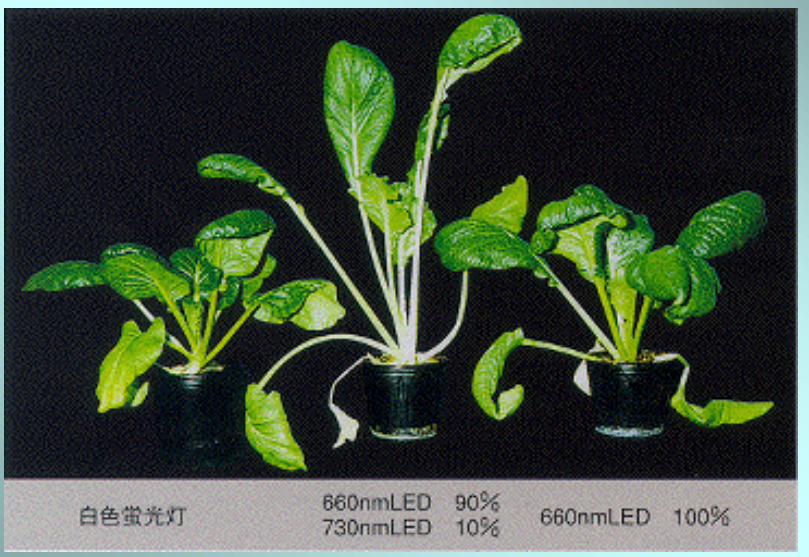
缺藍光，影響地下部形成



缺藍光，地上部纖細



缺藍光，卻有紅外光，更纖細

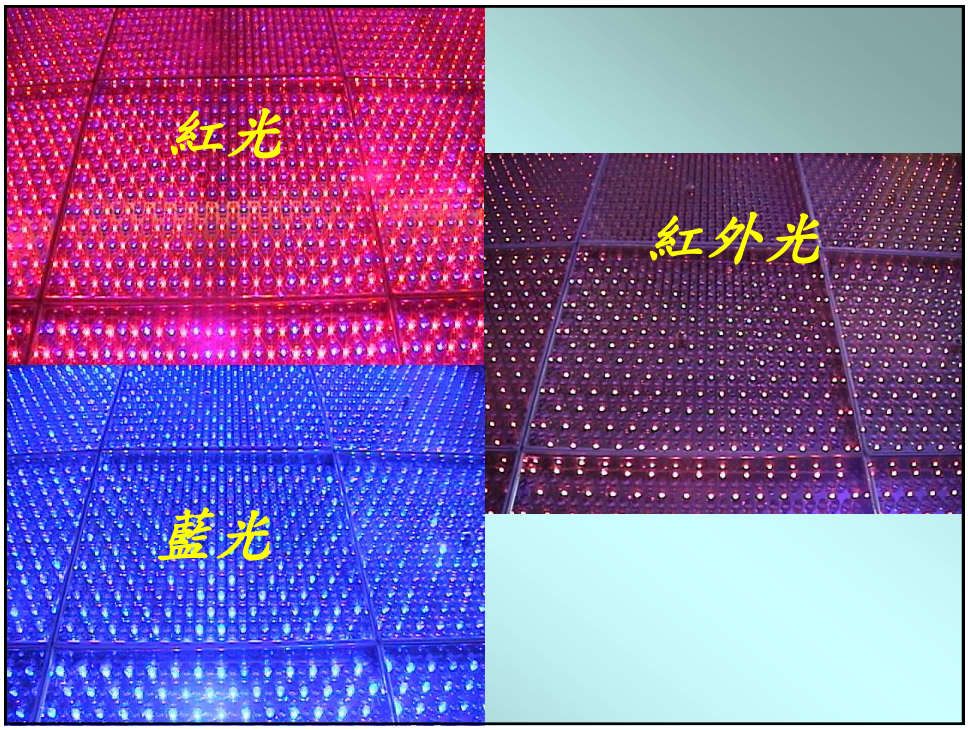


Marshall Space Flight Center

美國NASA

配備
紅光
紅外光
藍光
的
植物生長箱

植物生長箱光源



日本的LED蔬菜工廠

- 植物栽培用光源爲改良型水冷式紅色LED（660 nm）。
- 以薄膜水耕法(NFT)生產生菜、芹菜等葉菜，生產能力爲5900株/日，150萬株/年。

待續

植物工廠地上部與地下部環境控制

風、光、水、養、氣