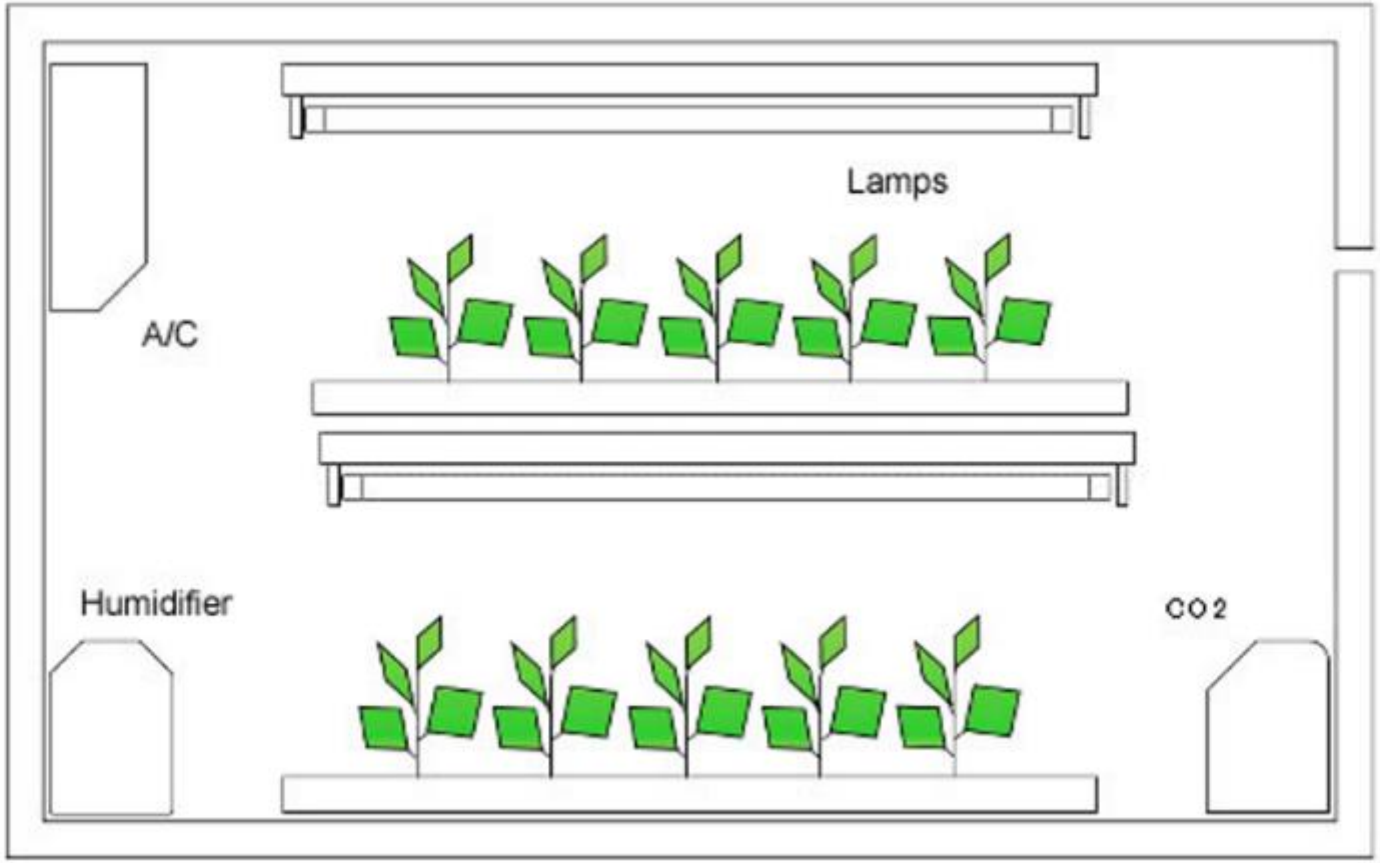


TOTAL PERFORMANCE EVALUATION OF PLANT FACTORY WITH ARTIFICIAL LIGHTING (PFAL)

Wei FANG, Ph.D., Professor
Dept. of Biomechatronics Engineering
National Taiwan University

TOTAL PERFORMANCE EVALUATION

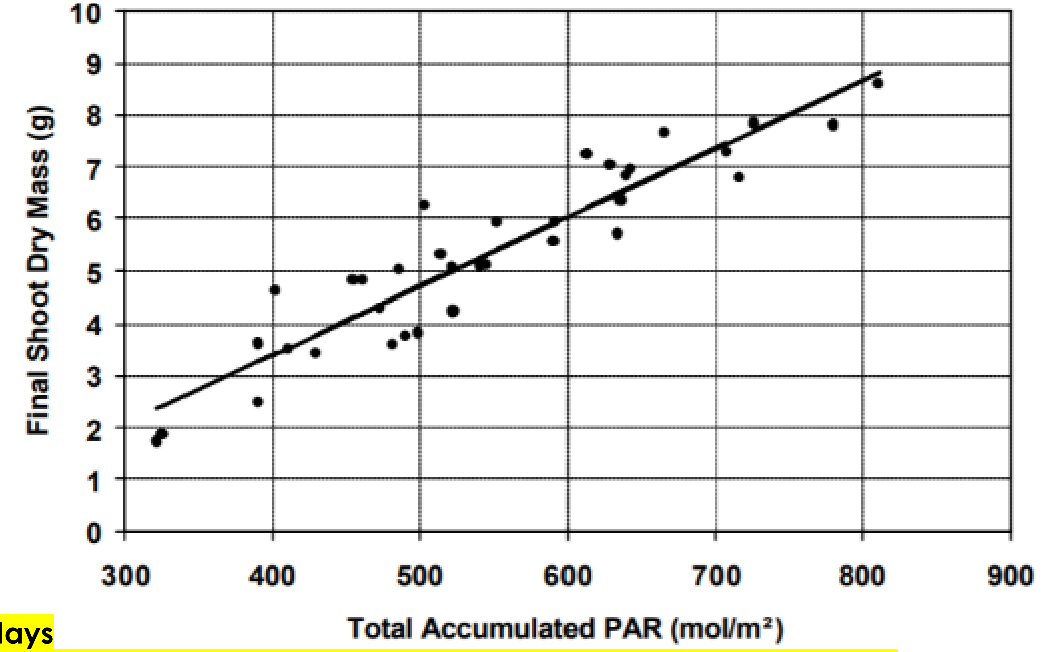
- **Area** required to harvest 1 kg
- Photons required to harvest 1 kg
- Labor required to harvest 1 kg
- Electricity cost required to harvest 1 kg

Area required to harvest 1 kg of vegetable

	播種	育苗	育成		播種	育苗	育成		播種	育苗	育成	
Tray or Plate (TorP)	穴盤	浮板	浮板	累計	端盤	浮板	浮板	累計	穴盤	浮板	浮板	累計
Area, m2	0.18	0.54	0.54		0.18	0.54	0.54		0.18	0.54	0.54	
Density, plt/TorP	128	64	32		300	64	32		128	64	32	
Density, plt/m2	711	119	59		1667	119	59		711	119	59	
Duration, days	14	7	14	35	7	14	14	35	7	7	21	35
Area per 1000 plts	1.41	8.44	16.88	26.7	0.60	8.44	16.88	25.9	1.41	8.44	16.88	26.7
Area ratio	0.1667	1	2		0.0711	1	2		0.16667	1	2	
Area * days	19.7	59.1	236.3	315.0	4.2	118.1	236.3	358.6	9.8	59.1	354.4	423.3
Area&Time ratio	0.3	1.0	4.0		0.036	1.0	2.0		0.1667	1.0	6.0	

Assuming 100 g per plant, 10 plants can reach 1 kg
Area required for 1000 plants is 26.7 m^2, thus harvesting 1 kg, you need 26.7*10/1000 = 0.267 m^2

Photons required to harvest 1 kg of vegetable



35 days						
DLI =	8.57	11.42	14.3	17.14	20	22.85

Figure 4. Linear relationship between lettuce (cultivar Ostinata) final shoot dry mass and total accumulated light levels (since seeding). The equation for the line is: DM = -1.886 + 0.0132(Accumulated light); R^2 = 0.87.

TLI = DLI * Days

45 g DM = -1.886 + 0.0132 (TLI)

TLI = 3552 mol/m^2

DM = 0.045 * FM

FM = DM / 0.045

100 g FM * 0.045 = 4.5 g DM

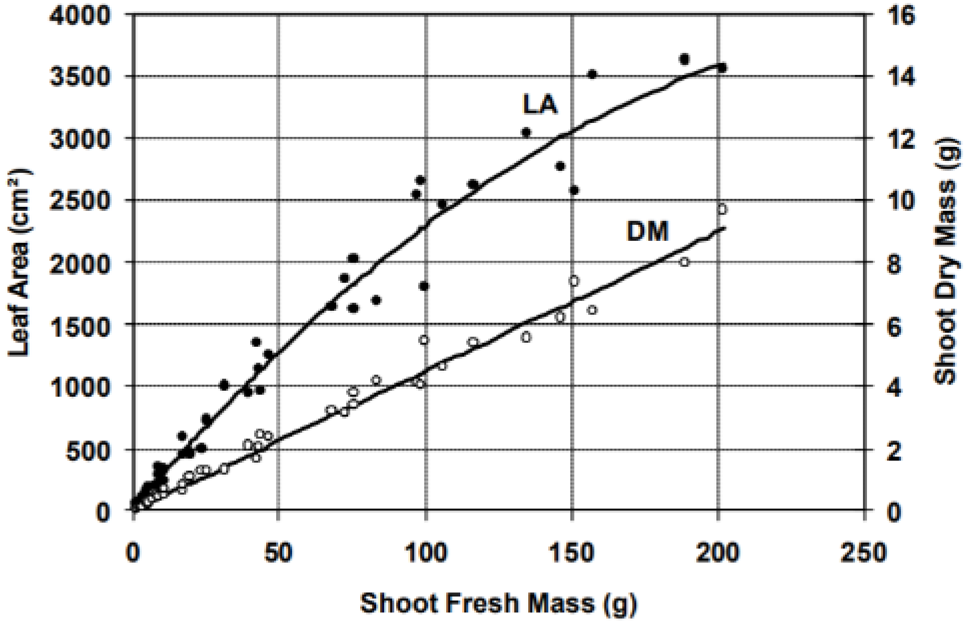
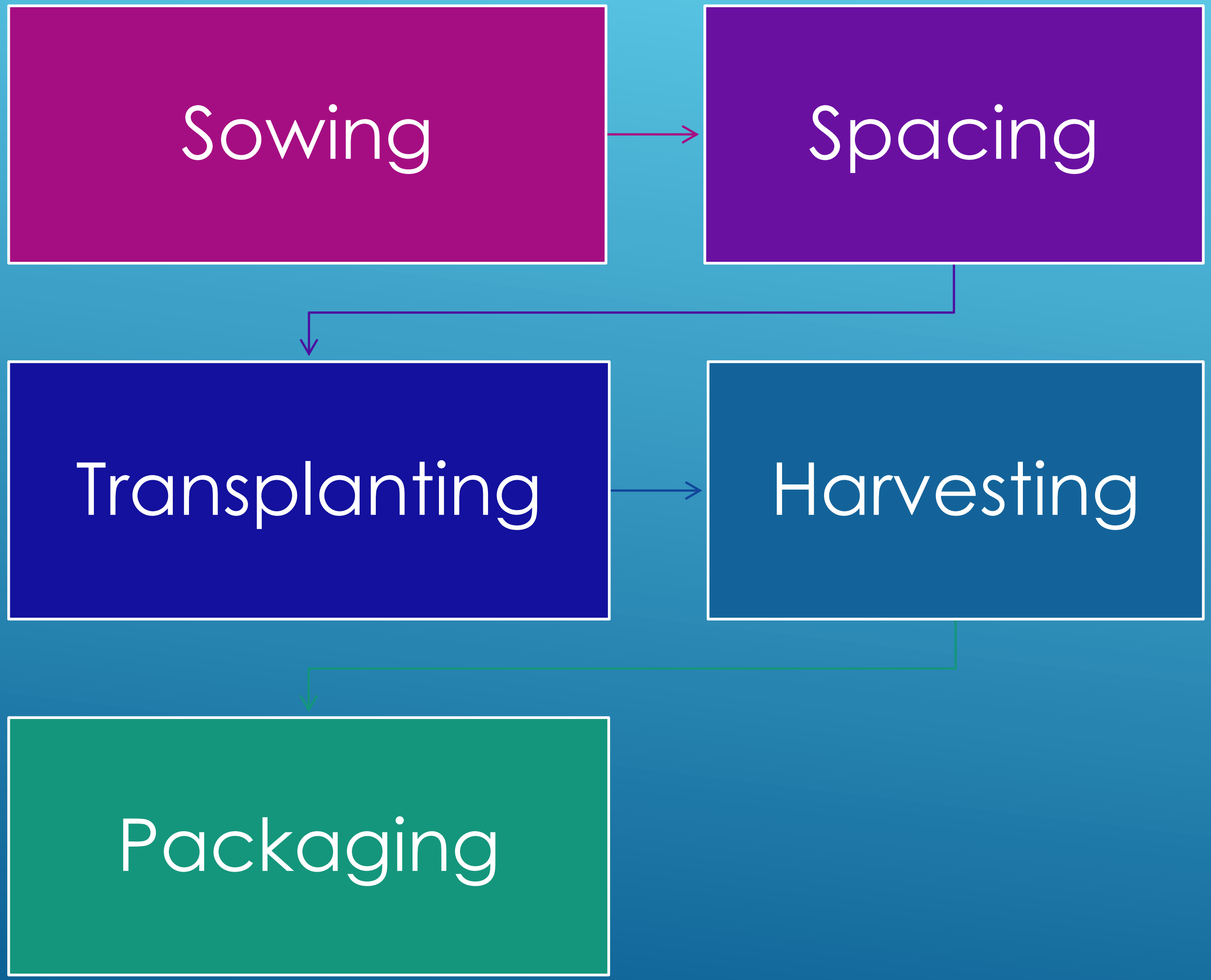


Figure 5. Correlations between lettuce (cultivar Ostinata) leaf area and shoot dry mass, and between shoot dry and fresh mass. The equation for the leaf area line is: LA = 22.77 + 27.57(FM) – 0.04880 (FM)^2; R^2 = 0.97. The equation for the shoot dry mass is: DM = 0.045(FM); R^2 = 0.97.

Labor required to harvest 1 kg of vegetable



Need to have the operating time for all manual operated task.

OP.time(i) = Convert all values into per plant basis, in min/plt.

TOP.time = Sum of OP.time(i) of all task.

TOP.time * number of plants per 1 kg

Electricity cost required to harvest 1 kg of vegetable

To harvest 1 kg, value of kWh needed = 1000 / EY

Where EY in g_FW/kWh (**EY will be introduced later**)

Given utility fee (U, in $/kWh)

Electricity cost on light to harvest 1 kg

= 1000 * U / EY

Given COP of AC,

Electricity cost on light and AC

= 1000 * U * (COP+1)/ (COP * EY)

TOTAL PERFORMANCE EVALUATION

PY, EY and OLe

PVr and P2Cr

PY

(g mol^{-1})

EY

(g kWh^{-1})

OLe = EY/PY

PVr

(Price / Varcost)

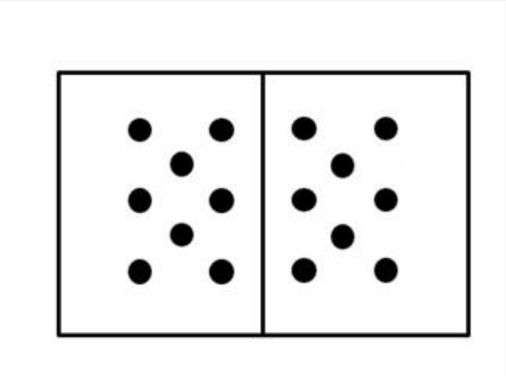
P2Cr

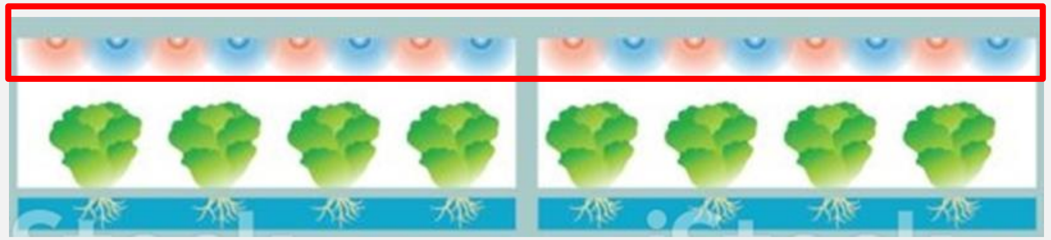
(Price / (varCost+fixCost)

PHOTON YIELD (PY)

1. From sowing to harvest, calculate DLI of each stages (mol/m2/day), times duration of each stage to get TLI (mol/m2)
2. Divide TLI by the density (plts/m2) of each stage to derived mol/plt of each stages.
3. Sum up for all stages
4. Derive PY by divide the avg. harvested FM (g/plt) to (mol/plt) to derive **g FM/mol**.

Photon Yield, PY





- Area of cultural bed
- Cropping density

- Daily Light Integral (DLI) in mol day^{-1} m^{-2}
  - PPFD (400-700 nm, PAR, µmol m^{-2} s^{-1}) ×Light period (h d^{-1}) ×3.6/1000
- Total light integral per plant at stage i, TLI(i) in mol/plant
  - TLI(i) = DLI(i) × Duration(i) / cropping density(i)
- Overall Total Light Integral per plant $\mathbf{OTLI = \sum_{i=1}^{n} TLI(i)}$

PY (g mol^{-1}) = g_FW / OTLI (g/plant / mol/plant)

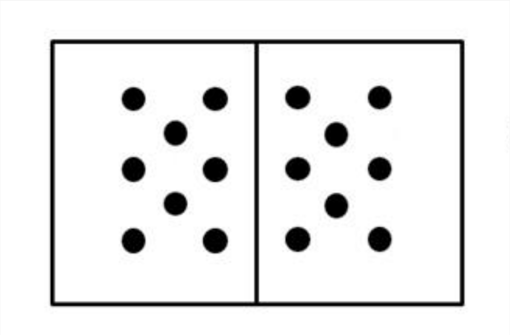
PY_A (mg mol^{-1}) = mg.Anthocyanin/plant / OTLI (mol/plant)

PY_D (mg mol^{-1}) = mg.Vit.E/plant / OTLI (kWh/plant)

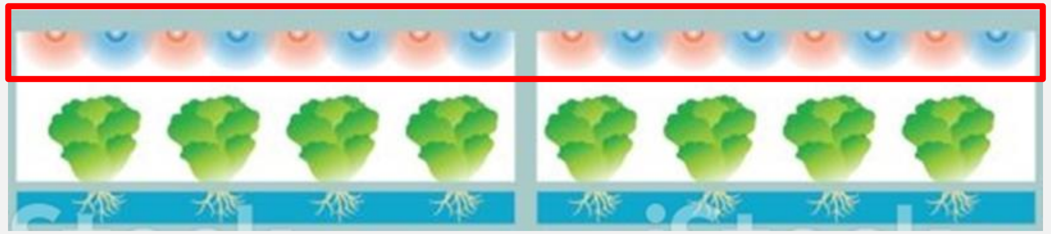
ENERGY YIELD (EY)

1. From sowing to harvest, calculate power consumption (PC) per unit area of each stages (kWh/m2/day), times duration of each stage to get TPC (kWh/m2), then divided by the density (plts/m2) of each stage to derived kWh/plt of each stages.
2. Sum up for all stages
3. Derive EY by divide the avg. harvested FM (g /plt) to (kWh/plt) to derive **g FM/kWh**.

Energy Yield, EY



- Area of cultural bed
- Cropping density



- Power consumption per unit area, PCA (W m^{-2})
  - Power consumption per lamp (W) × number of lamps per unit area (m^{-2})
- Daily power consumption per unit area per day, DPI (kWh d^{-1} m^{-2})
  - PCA (W m^{-2}) × light period (h d^{-1}) / 1000
- **Total power integral per plant, TPI(i)** (kWh/plant)
  - DPI(i) × duration(i) / cropping density(i) (plant m^{-2})
- Overall Total Power Integral per plant **OTPI** $= \sum_{i=1}^{n} TPI(i)$

EY (g/kWh)= gFW (g/plant) / OTPI (kWh/plant)

EY_A (mg/kWh)=mg Anthocyanin (mg/plant) / OTPI (kWh/plant)

EY_D (mg/kWh)= mgVit.E/plant / OTPI

DETAILS TO EY CALCULATION

- Stage 1
  - duration (d):14
  - Light period (h/d): 24
  - Power (W) per lamp :18
  - Area : 0.6 m^2
  - No.lamps : 7 tubes
    - No.lamps/m^2: 12.73 tubes/ m^2
  - No.plants: 433 plts
    - Cropping density: 772 plt/m^2
- Stage 2
  - …………

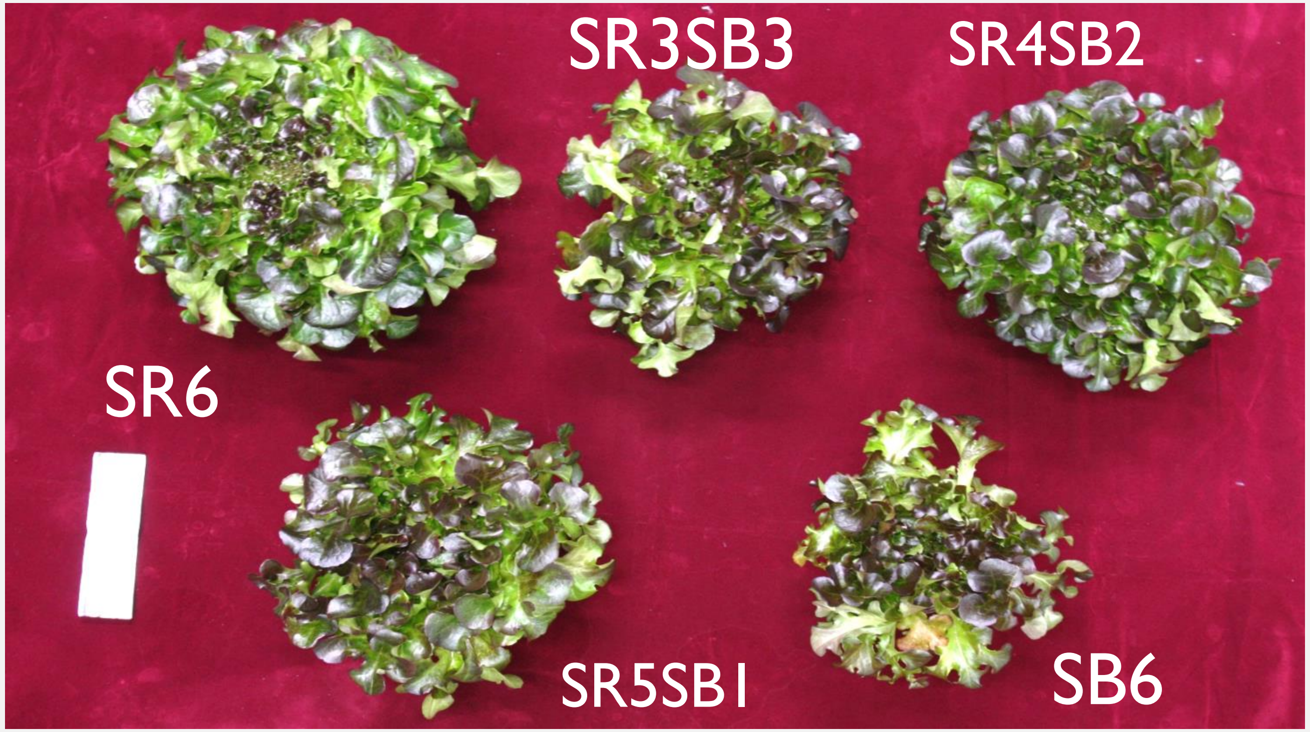
TPI(1) (kWh/plant) = 14*24*18*12.73/772/1000=0.0997

$$\text{TPI(i)} = \frac{d * \frac{h}{d} * \frac{W}{m^2}}{plant/_{m^2}} = \frac{Wh}{plant}$$

$$\textbf{OTPI} = \sum_{i=1}^{n} \boldsymbol{TPI(i)}$$

EY(g/kWh)= FW (g/plant) /OTPI

Treatment	g/plt	Anthocy. mg/g	Anthocy. Content per plant mg/plt	EY g/kWh	EY_A mg/kWh	PY gFW/mol	PY_A mg/mol
SR5	54.06	0.0138	0.74	47.03	0.65	11.01	0.15
SR3SB2	38.77	0.0168	0.65	32.29	0.54	7.89	0.13
SR4SB1	50.12	0.0124	0.62	42.65	0.53	10.20	0.13
SB5	22.14	0.0179	0.40	30.58	0.55	4.51	0.08



PY Photon Yield of fresh mass

PY_A Photon Yield of Anthocyanin

EY Energy Yield of fresh mass

EY_A Energy Yield of Anthocyanin

Overall Lighting Efficacy, in mol/kWh (OLe) = EY / PY

Treatments	FW gFW/plt	Anthocya. concentration mg/g	Anthocya. content mg/plt	EY gFW/kWh	EY_A mg/kWh	PY gFW/mol	PY_A mg/mol	OLe mol/kWh
SR6	108.30	0.0138	1.49	67.15	0.93	15.72	0.22	4.271
SR3SB3	70.11	0.0149	1.04	43.47	0.65	10.17	0.15	4.272
SR4SB2	88.70	0.0147	1.31	55.00	0.81	12.87	0.19	4.273
SR5SB1	87.75	0.0197	1.73	54.41	1.07	12.73	0.25	4.274
SB6	43.24	0.0159	0.69	26.81	0.43	6.27	0.10	4.276

EFFECTS OF OLED AS LIGHT SOURCE TO THE GROWTH AND ANTIOXIDANTS-CONCENTRATION OF TAIWAN JEWEL ORCHID

Treatment	g/plt	Gastrodin concentration μg/g	Gastrodin content μg/plt	DPPH concentration vit C mg/g	DPPH content mg/plt	EY g/kWh	EY_G μg/kWh	EY_D mg/kWh
OLED 1	9.6	12.7	121.3	0.03	0.28	6.8	86.3	0.20
OLED2	10.6	13.1	138.5	0.04	0.42	4.8	62.0	0.19
CW	10.9	5.0	54.0	0.03	0.28	7.0	34.7	0.18

Treatment	PY g/mol	PY_G mgGastrodin/mol	PY_D mgDPPH/mol	OLe
OLED 1	3.17	40.24	0.09	2.145
OLED2	3.52	45.96	0.14	1.363
CW	3.60	17.93	0.09	1.944

Lighting Efficacy (Le) vs. Overall Lighting Efficacy (OLe)

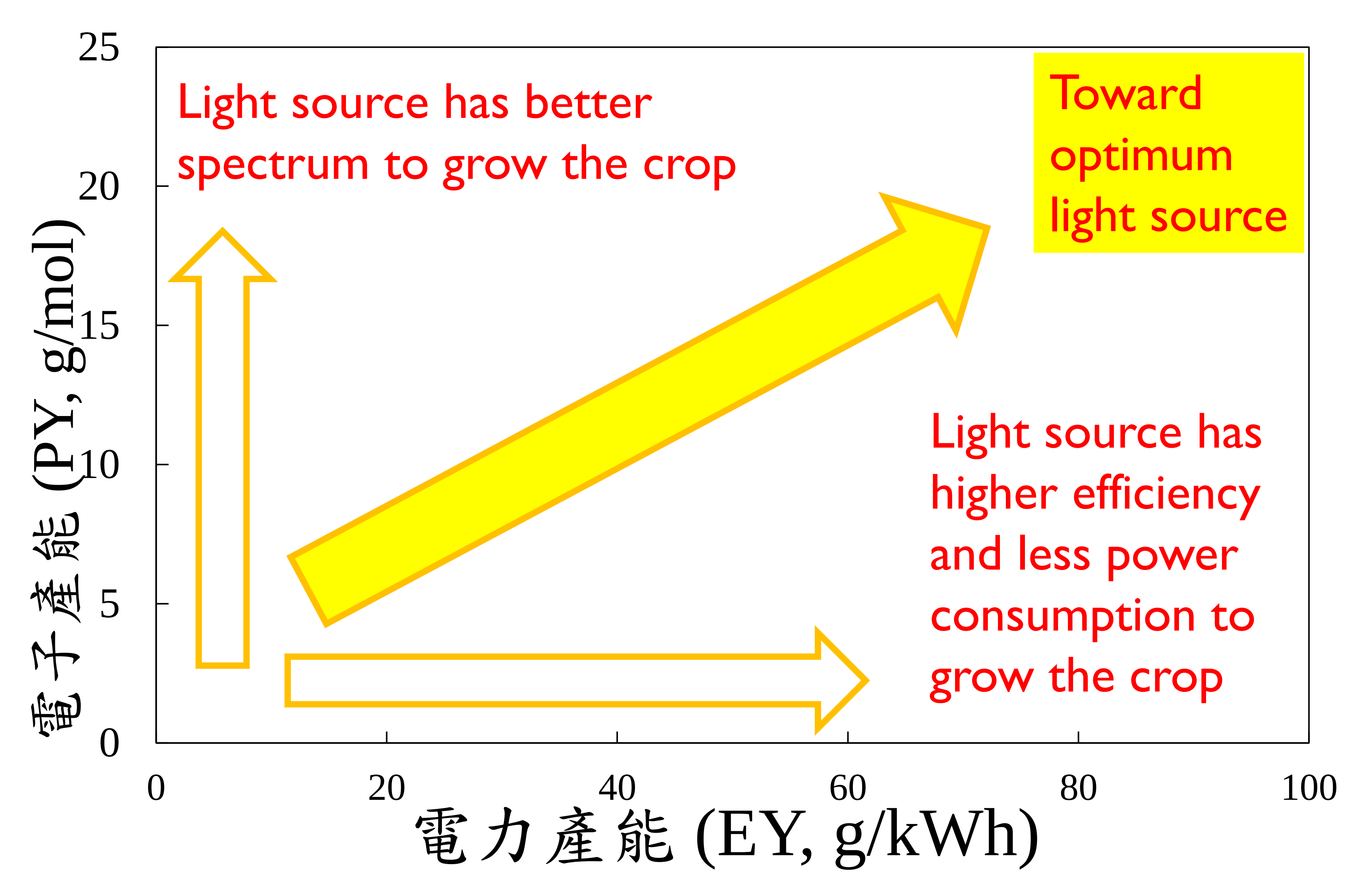
- Le in μmol/J, measured after the installation of light source prior to the growth of any plants.

- OLe in mol/kWh, calculated after the growth, allow the adjustment of light source and light period during any growth stages.

- If no alteration of light source during the growth period, two terms have the relationship as shown below:

$$Le = OLe / 3.6$$

TPE diagram: PY vs. EY



$$\text{PV ratio} = \frac{Price\ of\ the\ product\ (\$/g)}{Variable\ cost\ (\$/g)}$$

Price of the product vs. Variable cost on lighting

$$\text{P2C ratio} = \frac{Price\ of\ the\ product\ (\$/g)}{variable\ Cost + fixed\ Cost\ (\$/g)}$$

Price of the product vs. variable Cost + fixed Cost on lighting

PVr

EY (g/kWh) → Market Value (mVal) / Electricity Fee on Lightg

蔬菜	價格 (元/g)	參考
紫甘藍芽	0.9	綠藤生機
青花菜芽	0.9	
蘿蔔嬰	0.3	
萵苣類	1.0	庭茂
金線連	15.0	
芝麻葉	7.2	
機能性萵苣 (低鉀、高花青素)	2.0	日本富士通
萵苣有機水耕	1.3	

$$PVr = Pg / Vg$$

$$V_g = U_{kwh} / EY$$

$$PVr = P_g * EY / U_{kwh}$$

where,

PVr: PV ratio, in $/$

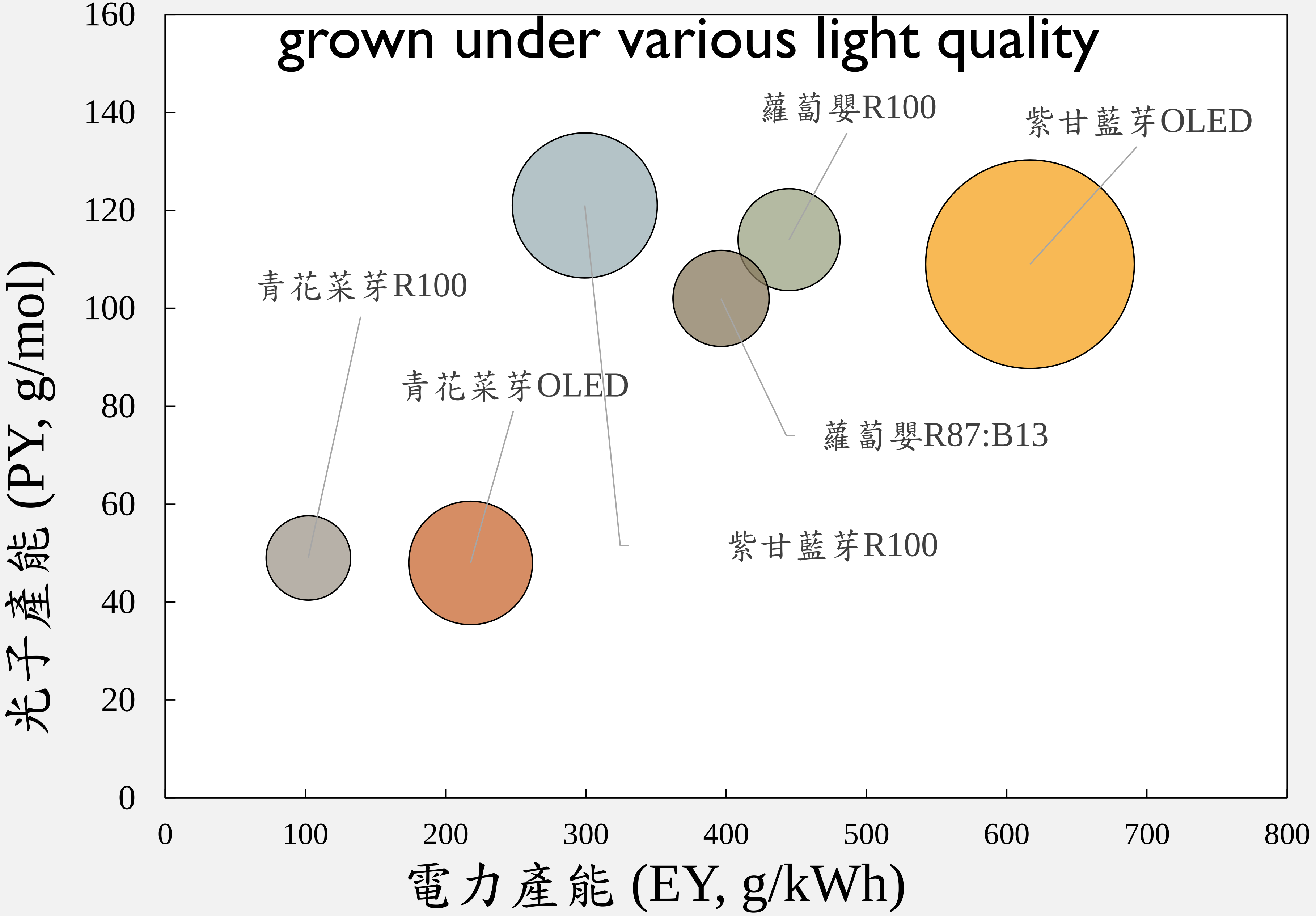
P_g : Price per gram, in $/g

V_g : Variable cost per gram on lighting, in $/g

U_{kwh} : Utility.fee per kWh, in $/kWh

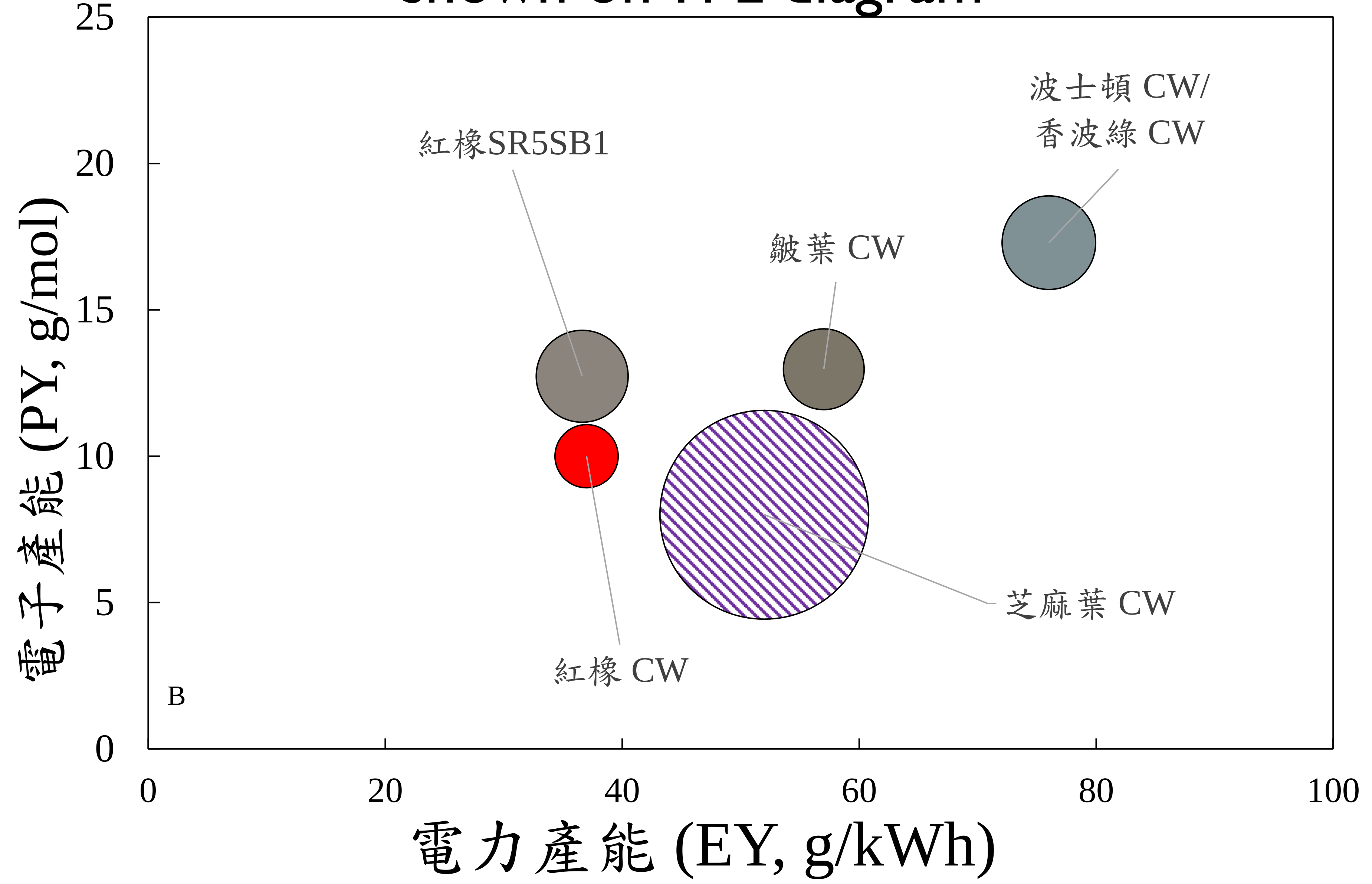
EY: Energy Yield, in g/kWh

EY, PY and PVr (**TPE diagram**) of different sprouts grown under various light quality

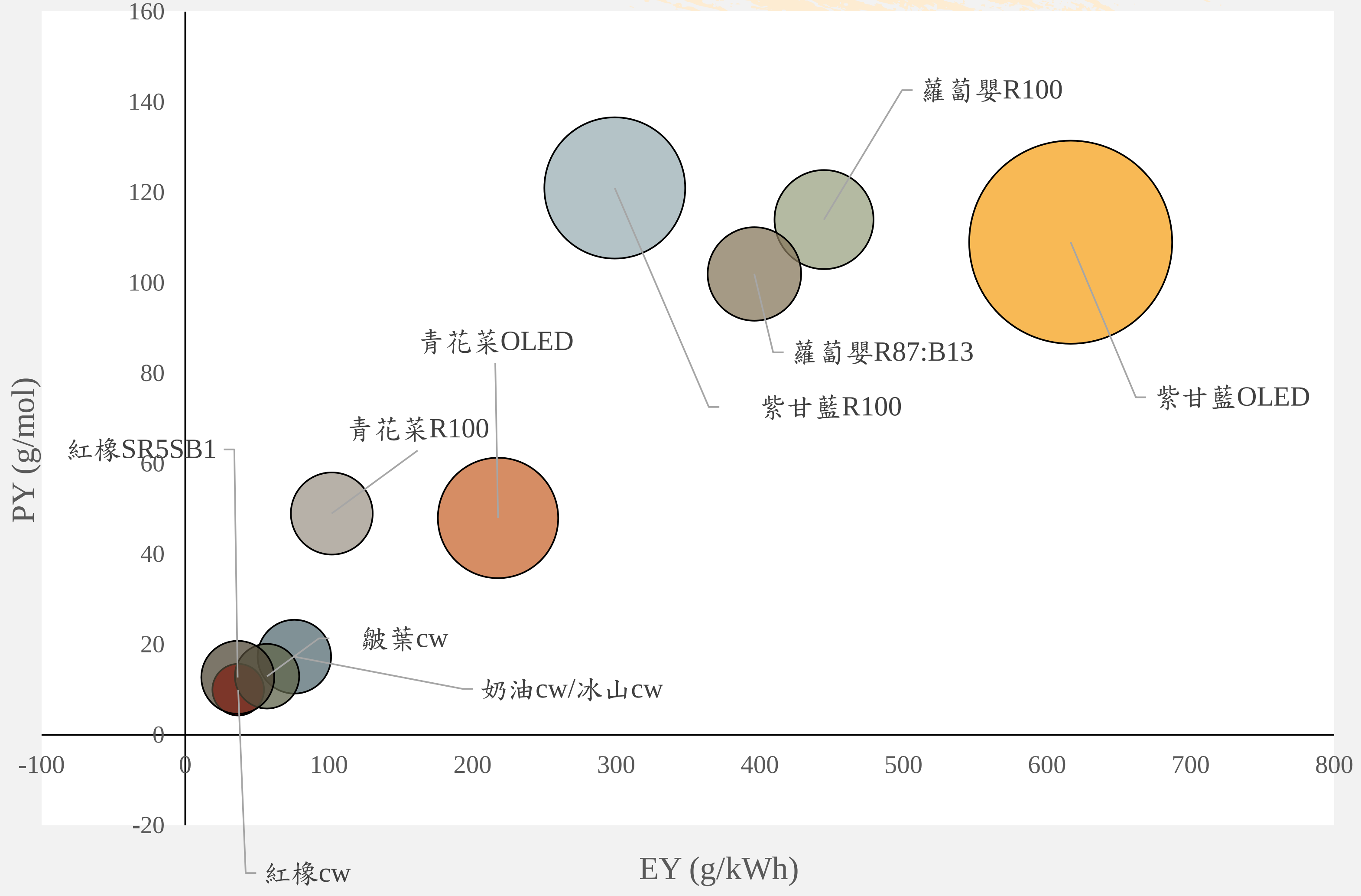


PVr is the radius of the circle

Lettuce and rucola grown under various light quality shown on TPE diagram



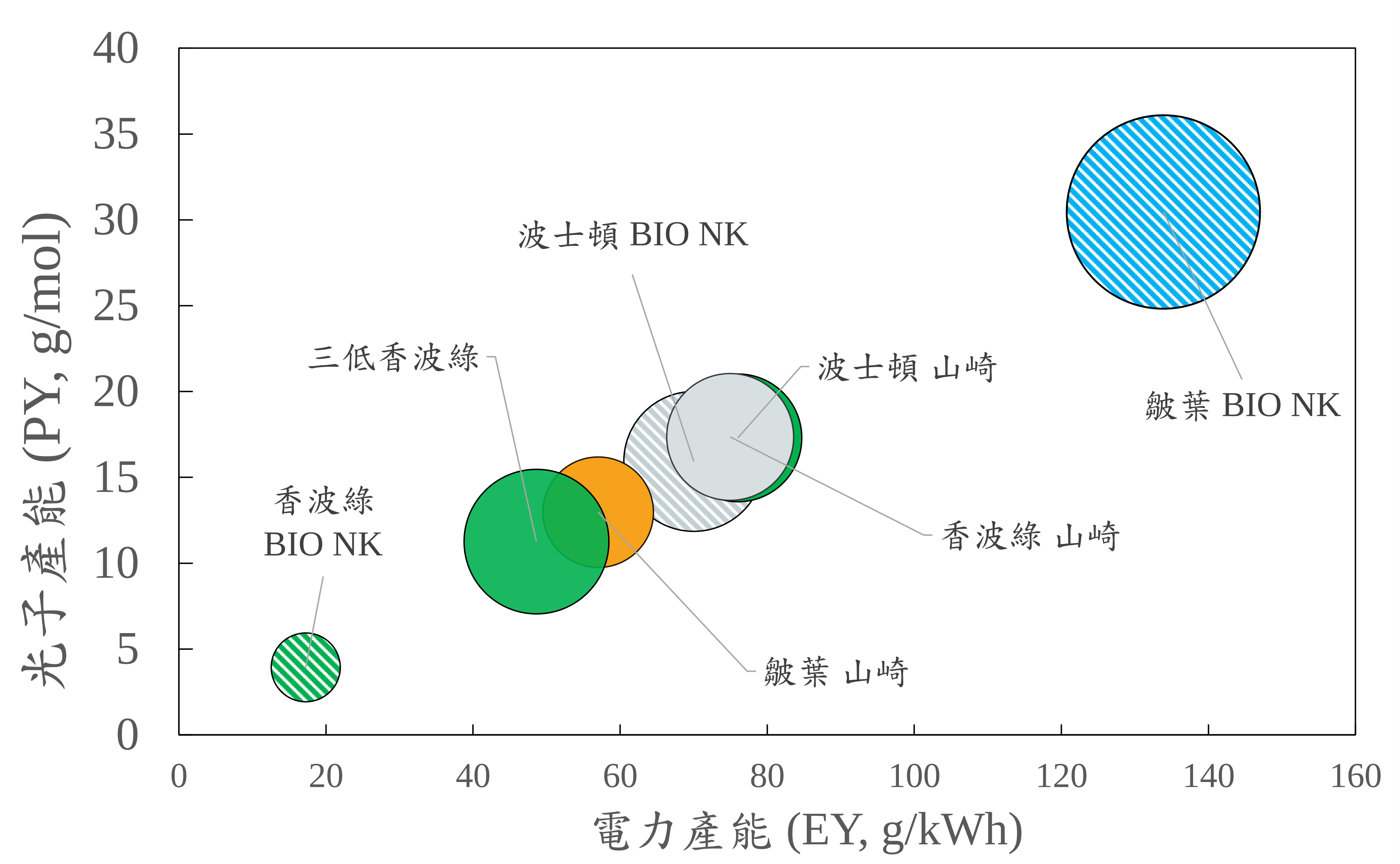
Lettuce and sprout grown under various light quality shown on TPE diagram



Impact of light quality on EY, PY and PVr

vegetable	Artificial Light: Light quality	Artificial Light: Power ($W \cdot m^{-2}$)	EY (g/kWh)	PY (g/mol)	PVr	Relative PVr
紫甘藍芽	OLED	15.8	617	109	231	7.3
紫甘藍芽	R_{100}	35.8	299	121	112	3.5
蘿蔔嬰	R_{100}	72.7	445	114	56	1.8
蘿蔔嬰	R_{87}:B_{13}	71.5	396	102	50	1.6
青花菜芽	R_{100}	70.6	102	49	38	1.2
青花菜芽	OLED	31.8	218	48	82	2.6
芝麻葉	CW	218.18	21	9	63	2.0
香波綠萵苣	CW	185.14	75	17	32	1.0
紅橡萵苣	CW	185.14	37	10	15	0.5
皺葉萵苣	CW	185.14	57	13	24	0.8
紅橡萵苣	SR5SB1	126.39	37	13	31	1.0
波士頓萵苣	CW	185.14	76	17	32	1.0

Impact of nutrient solution on TPE diagram



Impact of nutrient solution on EY, PY and PVr

Lettuce	Nutrient solution	EY (g/kWh)	PY (g/mol)	PVr	Relative PVr
皺葉	BIO NK	134	30	50	2.3
皺葉	Yamazaki	57	13	16	0.7
波士頓	BIO NK	70	16	26	1.2
波士頓	Yamazaki	76	17	22	1.0
香波綠	BIO NK	17	4	6	0.3
香波綠	Yamazaki	75	17	21	1.0
香波綠	NTU_low_P	49	11	28	1.3

Vege.	treatment	EY (g/kWh)	PY (g/mol)	PVr	Relative PVr	Value-added
紫甘藍	OLED	617	30	162	7.4	高抗氧化力
	R_{100}	299	14	78	3.5	
青花菜	OLED	218	10	57	2.6	高抗氧化力
	R_{100}	102	20	27	1.2	
蘿蔔嬰	R_{100}	445	21	44	2.0	
	$R_{87}:B_{13}$	396	19	39	1.8	高抗氧化力
奶油萵苣	BIO N	49	11	18	0.8	民眾信賴
	BIO NK	70	16	26	1.2	
	山崎湛液	76	17	22	1.0	
	山崎潮汐	**148**	**24**	**42**	1.9	**高產量**
皺葉萵苣	山崎湛液	57	13	16	0.7	民眾信賴
	BIO N	82	19	31	1.4	
	BIO NK	134	30	50	2.3	
冰山萵苣	山崎湛液	75	17	21	1.0	
	低鉀萵苣	49	11	28	1.3	腎臟病人專用
紅橡	CW	37	10	10	0.5	
	SR5SB1	37	13	21	1.0	高花青素
芝麻葉	*山崎潮汐*	52	8	107	4.9	高產量/藥味

Drawbacks of PVr leads to a new index

- Only reflect the operating cost on electricity of lamps
- Did not includes the cost to purchase the lamps
- Can only be used for evaluation for cases with similar cost to purchase the lamps.

- A new index was developed to include the fixed cost on lamps.

From PVr to P2Cr

EY (g/kWh) → PVr Market Value (mValue) / Vari.Cost → P2Cr = mValue / (VC+FC)

$$P2Cr = \frac{FW\left(\frac{g}{plant}\right) \times Price(\frac{NT\$}{g}, ex: 1.25\ NTD/g)}{\left[oTPI\ \left(\frac{kWh}{plant}\right) \times utility\ Fee\ (\frac{NT\$}{kWh})\right] + oTD\ (\frac{NT\$}{plant})}$$

Factors affecting P2Cr

EY (g/kWh) ↑

PY (g/mol) ↑

Cultural practices

Market price ↑

$$P2Cr = \frac{FW \times Price}{[oTPI \times utility\ Fee] + oTD}$$

Power consump. of light ↓

Utility fee ↓

Cost on light source ↓

Overall Total Depreciation of LED (OTD, NT$/plant)

1. Usable life of LED (h): 35000 (assuming)
2. Cost of light source (NT$/piece)：WW=1500 ，RB=1000，CW=390
3. OTD: Overall Totally Depreciation of LED per plant (NT$/plant)

De(i) = Plamp(i) * Noflamp(i) / Lf(i)

TD(i) = De(i) * LP(i) * Days(i) / density(i)

$$OTD = \sum_{i=1}^{n} TD(i)$$

De(i): Depreciation of light source per unit area per hour,, in NT$ /m^2 h

Plamp: Unit price of lamp, in NT$/piece

Noflamp: number of lamps required per unit area, in piece/ m^2

Lf: usable life time of the lamp, in h

TD(i): Total depreciation of light source per plant in stage i, in NT$ / plant

LP(i) : Duration of light period per day, in stage i in h/day

Days(i): duration of days in stage i, in days

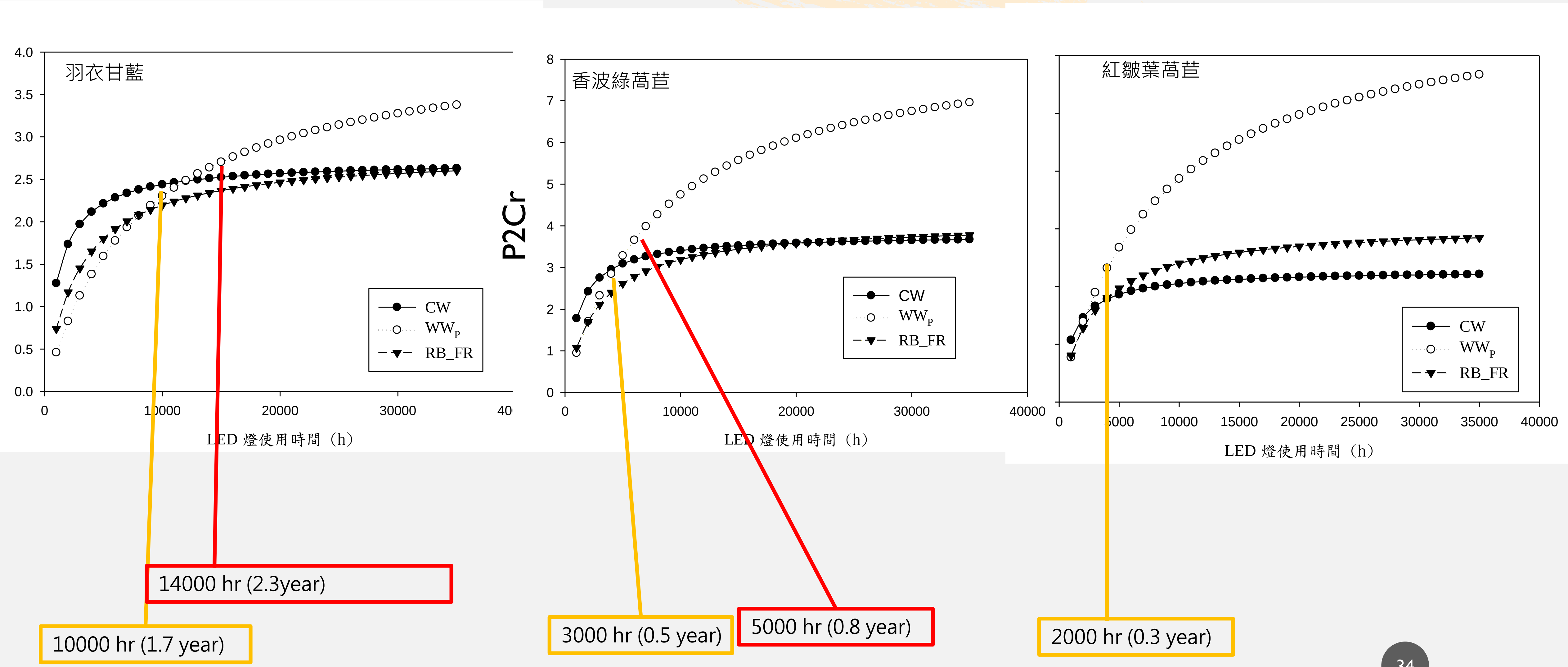
density(i): crop density sta stage i, in plant/m^2

Impact of types of light source and crop on index for T.P.E.

Light source	Crop	EY (g/kWh)	PY (g/mol)	P2Cr	OTPI (kWh/plant)	Vari.Cost (NT$/plant)	OTD=FixCost (NT$/plant)	LED Cost (NT$/tube)
CW	羽衣甘藍	26.6 d	6.39 d	2.6	7.69	26.9	0.9	390
	香波綠	37.1 c	8.92 b	3.7				
	紅皺葉	22.4 e	5.38 e	2.2				
WW_P	羽衣甘藍	40.7 c	5.29 e	3.4	4.16	14.6	3.3	1500
	香波綠	83.8 a	10.90 a	7.0				
	紅皺葉	68.3 b	8.22 b	5.7				
RB_FR	羽衣甘藍	27.5 d	6.83 d	2.6	7.94	27.8	2.2	1000
	香波綠	40.0 c	9.91 a	3.8				
	紅皺葉	30.1 d	7.47 c	2.8				

Means followed by the different letters in each column are significantly different at 5% level by LSD Test (n=5).

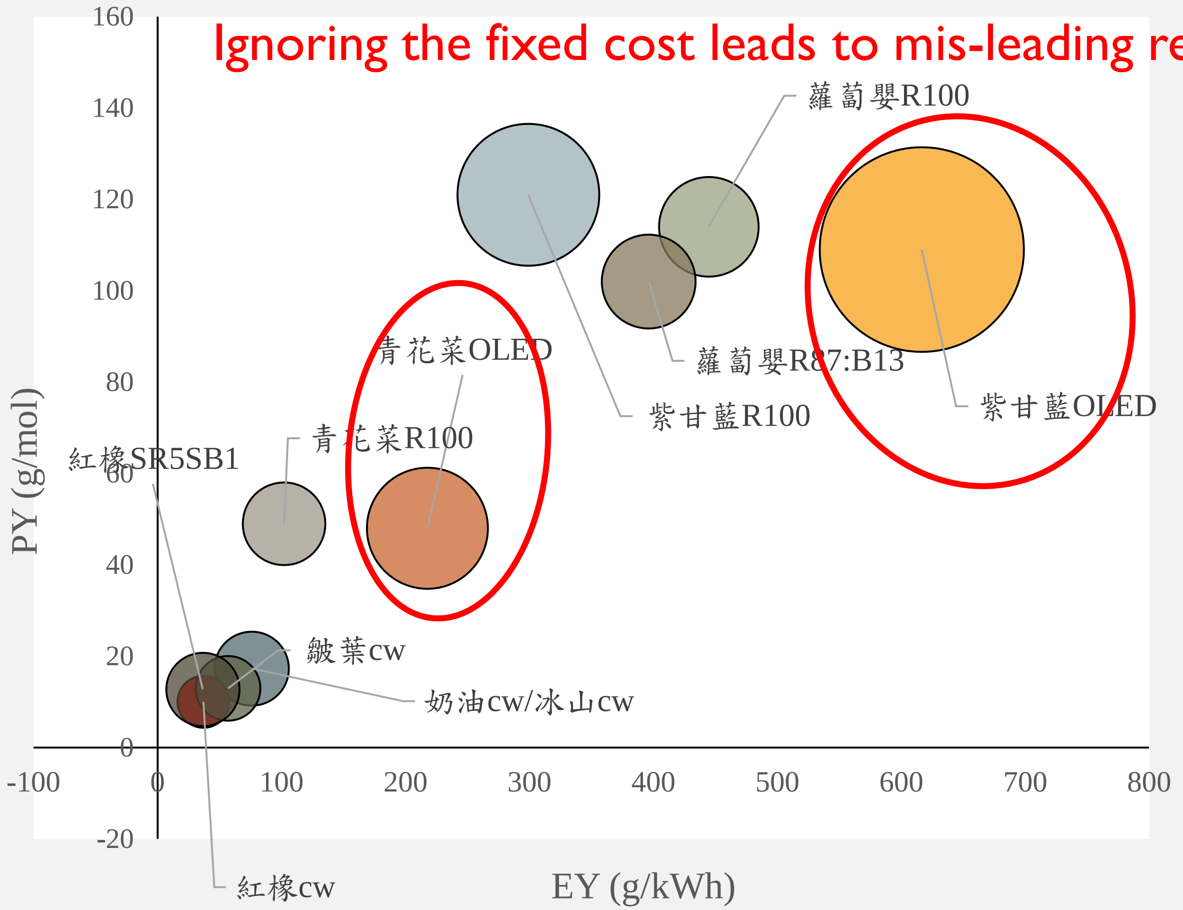
Impact of usable life of LEDs to P2Cr of 3 crops



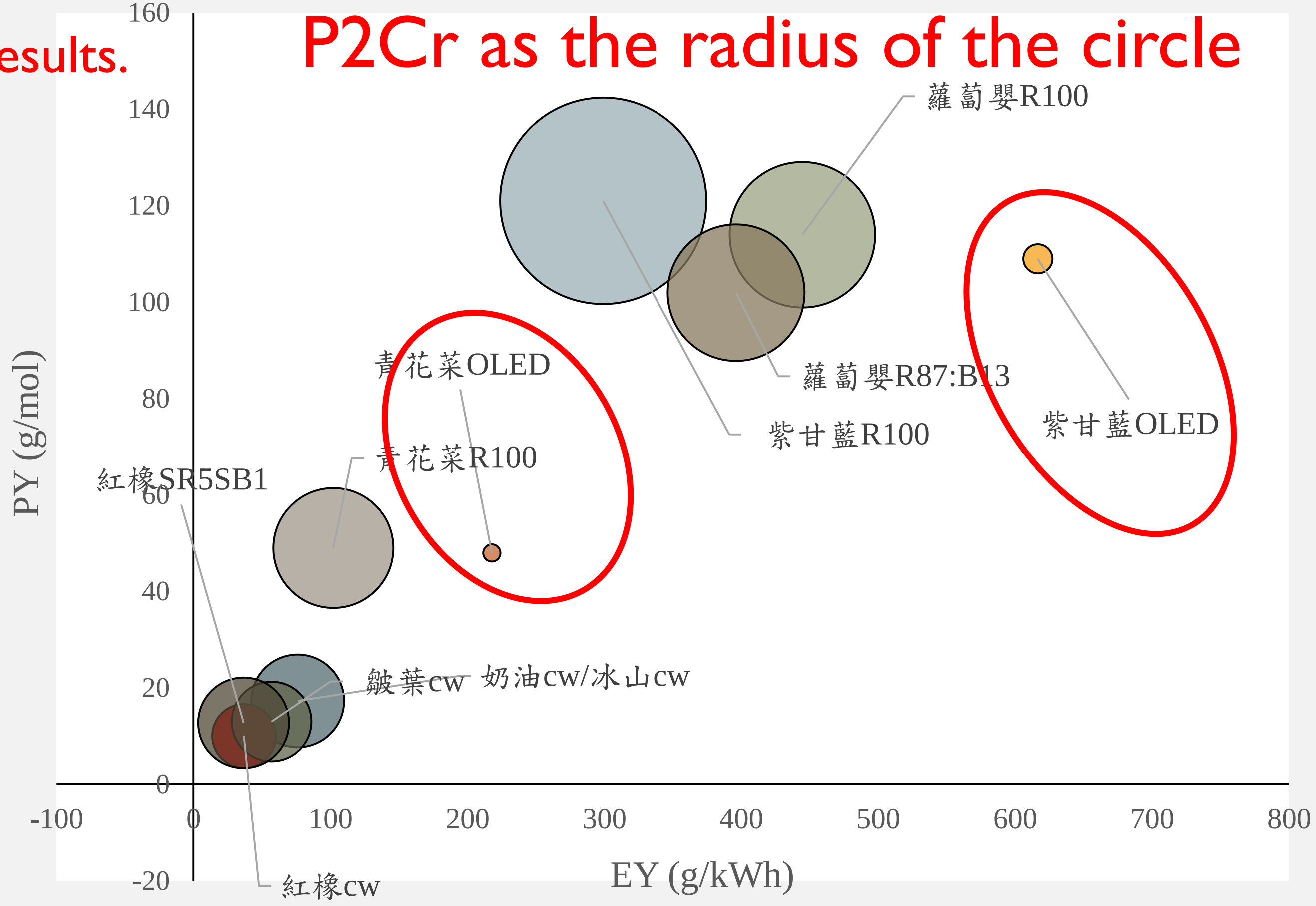
PVr vs. P2Cr on TPE diagram

PVr as the radius of the circle.

Ignoring the fixed cost leads to mis-leading results.



P2Cr as the radius of the circle



EY, PVr and P2Cr of leafy greens grown under various light quality and nutrient solution

Treatments	EY(g/kWh)	PVr	P2Cr	**OTD (NT$/plt)**
紫甘藍$_{OLED}$	617	231.3	2.4	226.1
紫甘藍$_{R100}$	299	112.2	112.2	0.001
蘿蔔嬰$_{R100}$	445	55.6	55.6	0.001
蘿蔔嬰$_{R87:B13}$	396	49.5	49.5	0.001
青花菜$_{OLED}$	218	81.7	0.9	226.1
青花菜$_{R100}$	102	38.3	38.3	0.001
皺葉$_{BIONK}$	134	72.5	51.2	0.86
皺葉$_{BION}$	82	44.6	31.5	0.86
三低冰山	49	40.5	29.8	0.86
奶油$_{BIONK}$	70	37.9	27.8	0.86
奶油	76	31.7	23.3	0.86
冰山	75	39.0	22.9	0.86
奶油$_{BION}$	49	26.4	19.4	0.86
皺葉	57	23.8	17.4	0.86
紅橡CW	37	15.4	11.3	0.86
紅橡SR5SB1	37	30.5	22.4	0.86

- OTD of OLED
- Price: 30000 NT$/plate
- Usable life: 200 h
- Piece required: 400 piece/m2
- Days：5 days
- Duration per day：12 h

- Depreciation per unit area = 30000*400*5*12/200 = 3600000 NT$/m^2

- Crop density: 15923 plant/m^2

- OTD = 3600000/15923 = 226.1

THE END