2 ZERO HUNGER

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

13 CLIMATE ACTION

11 SUSTAINABLE CITIES AND COMMUNITIES

western balkans urban agriculture initiative

Plant factories with artificial lighting

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Outline of the presentation

- What are PFALs?
- Resource use efficiency in indoor farming systems;
- Water Use Efficiency;
- Land Surface Use Efficiency;
- Energy Use Efficiency;
- Light Use Efficiency;
- Environmental assessment;
- Conclusive remarks.

Plant Factories with Artificial Lighting (PFALs)

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LED and vertical farming

The development of high power Light Emitting Diodes allowed for the growth of plant factories, enclosed places where plants are grown under non-natural light and perfectly controlled climate and root-zone conditions.

Introduction

In greenhouse production, even if high technologies are used, seasonal differences are still found, and control of one environmental parameter will result in changes in another parameter (e.g. when greenhouse vents are open to reduce heating, variations in atmospheric CO_2 are also experienced).

Vertical Farms (or Plant Factories with Artificial Lighting, PFALs) allow for season independent, full control of environmental factors.

Introduction

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Growing systems and environmental control

	Open fields	Low tech greenhouse	Hydroponic greenhouse	PFALs
Control of aerial zone	Very low	Medium	Medium	Very high
Stability of rootzone	High	High	Low	Low
Controllability of rootzone	Low	Low	High	High
Variations in yield and quality	High	Medium	Relatively low	Low
Initial investment per unit land area	Low	Medium	Relatively high	Extremely high
Yield	Low	Medium	Relatively high	Extremely high

Classification of four types of plant production systems by their environmental control features (readapted from Kozai, 2015. Plant Factory with Artificial Lighting, Springer).

PFALs are plant production facilities with a thermally insulated and nearly airtight warehouse like structure, where multiple culture layers with lamps on each shelf are vertically staked.

Introduction

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- Constant and high yield are possible throughout the year;
- No pesticide use, elevate land, water and nutrient use efficiency;
- Independent from solar radiation or soil fertility;
- Easier logistic chains;
- Wider choice of varieties and increased freshness;
- Lower food waste, more uniform quality, absence of dirt, high harvest index and reduced conservation.

Objectives of PFALs

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When compared with field production, the list of advantages are even higher (e.g. resilience to adverse climate), but…

… comparison shall also consider that …

- greenhouses are also adaptable to harsh climatic conditions;
- Investment costs for a plant factory are 4x to 10x higher than a high tech greenhouse;
- Artificial light requires electricity while a greenhouse benefit (at least partially) from solar radiation.

Objectives of PFALs

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Unique selling points of PFALs

- ✓ Can be nearer to consumers
  - ✓ Freshness
  - ✓ Other (tastier) varieties
- ✓ Less need for crop protection
  - ✓ Safer food
- ✓ Higher productivity
  - ✓ On-demand delivery possible
  - ✓ Less need for area
- ✓ Higher water use efficiency

Why only lettuce?

- Small volume, short in height (30 cm or less for easy vertical cultivation)
- Not requiring insect pollination
- High harvest index
- Growing well under relatively low light intensity and easy photoperiod management.

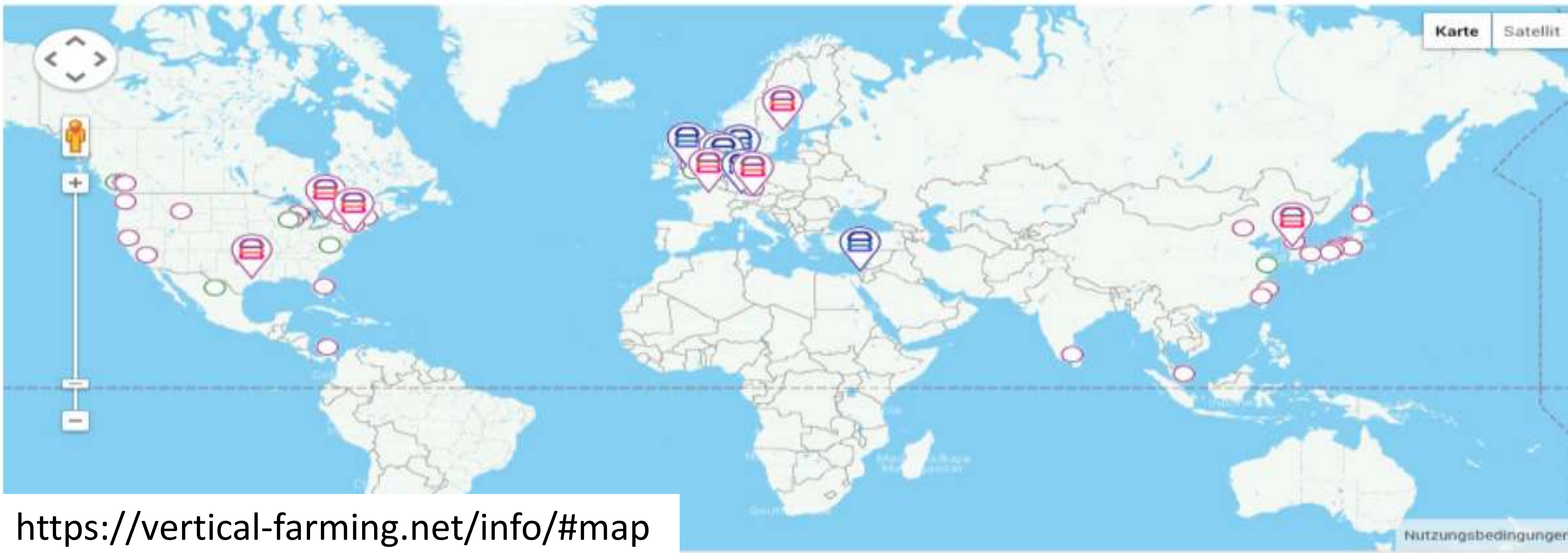
Which other crops could be grown?

- ✓ Seedlings of horticulture/floriculture crops;
- ✓ Microgreens and sprouts;
- ✓ Medicinal plants with improved metabolite content;
- ✓ Cash crops with high values (e.g. Cannabis) and legal requirements for cultivation indoor;
- ✓ Tropical/exotic crops (need for accurate climate control);

MedMen cannabis production in Los Angeles, USA

Worldwide PFALs distribution

The application of indoor farming technologies takes place in several regions of the world—mainly in Asian (42%), European (30%) and North American (21%) countries.



https://vertical-farming.net/info/#map

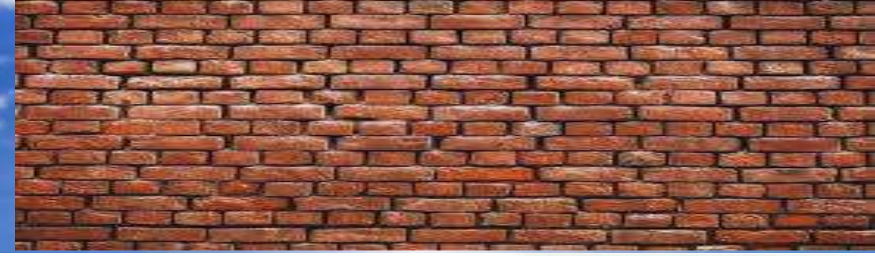
The market is expected to reach a global value of 5.80 billion USD by 2022 (MarketsAndMarkets, 2019).

Typologies of plant factories

Container type plant factory

Warehouse type plant factory

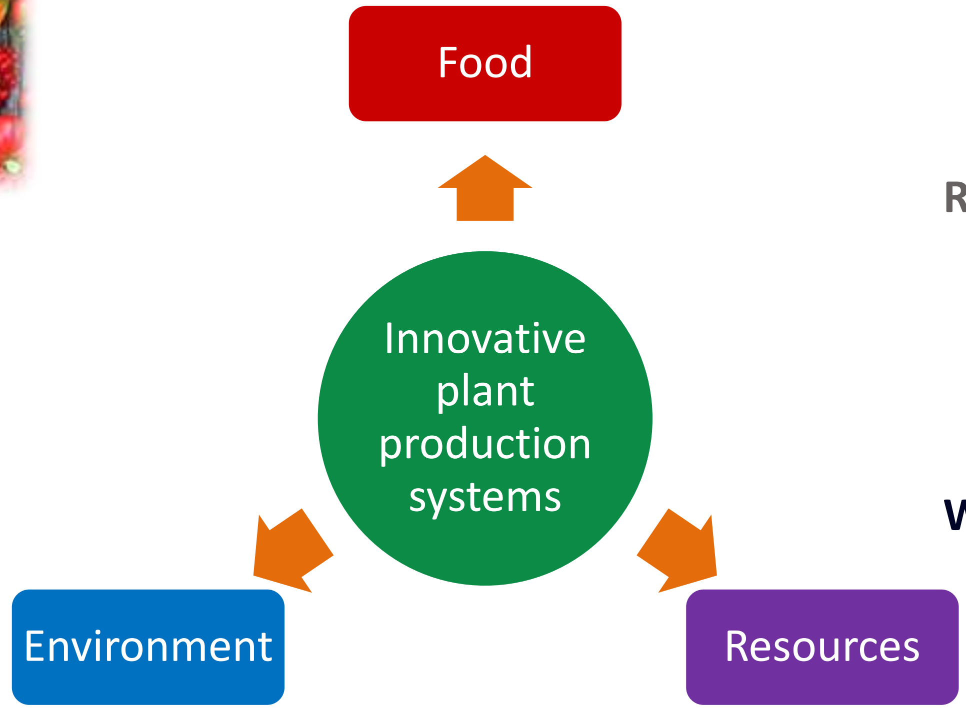
Resource use efficiency in indoor farming systems



Food insecurity

Global warming

Soil degradation and desertification



Reduced land availability

World population growth

Water scarcity

Limited fossil fuels availability

Kozai et al. 2019. Towards sustainable plant factories with artificial lighting (PFALs): from greenhouses to vertical farms. In Achieving sustainable greenhouse cultivation. Marcelis and Heuvelink.

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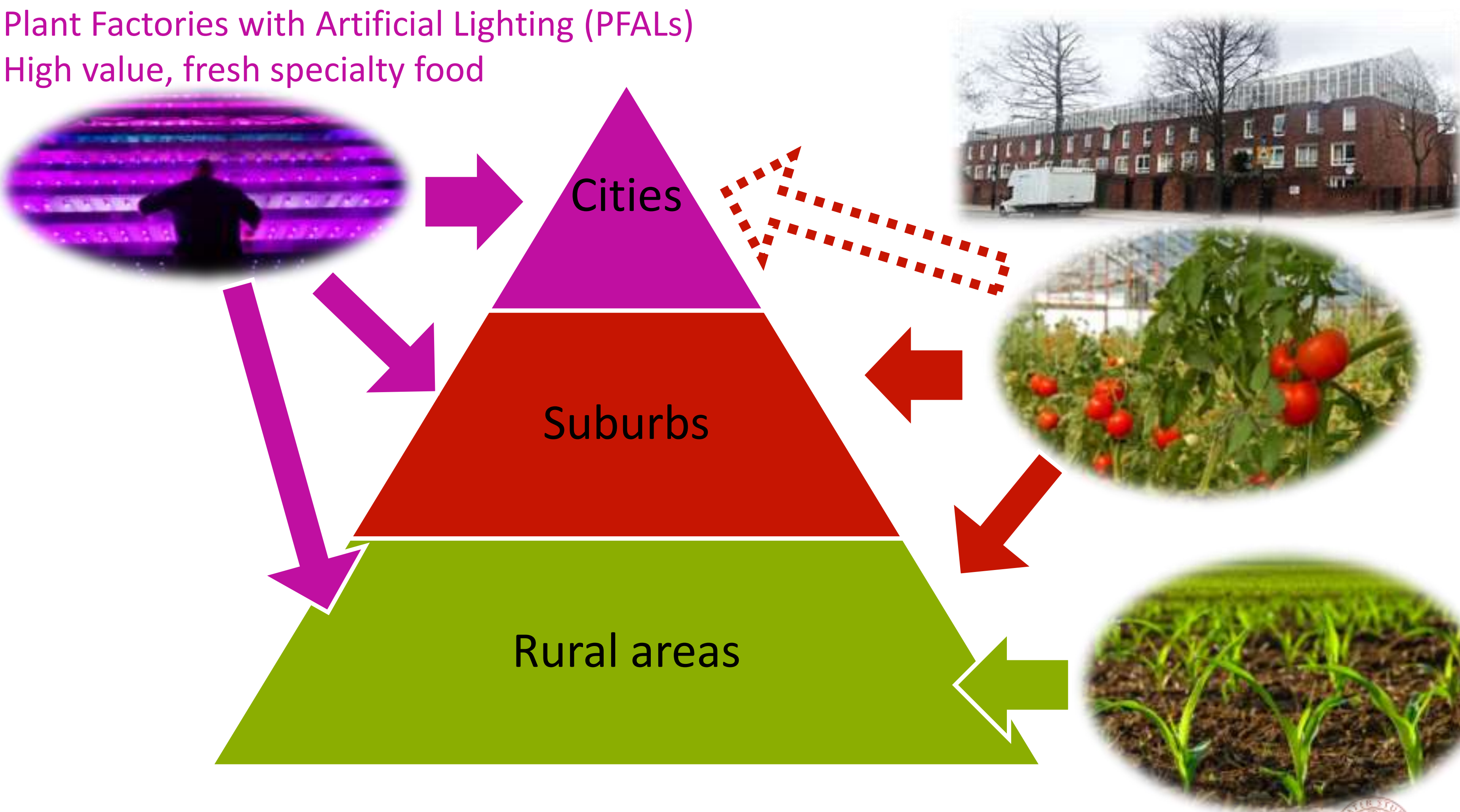
Plant production systems typologies



Kozai et al. 2019. Towards sustainable plant factories with artificial lighting (PFALs): from greenhouses to vertical farms. In Achieving sustainable greenhouse cultivation. Marcelis and Heuvelink.

INDOOR FARMS

Stable food production

By controlling light, humidity and temperatures, plant growth is independent from external climate.

Space and resource saving

By exploring the vertical dimension large quantities of food may be produced within small surfaces.

Thanks to hydroponics, water use is reduced up to -95%.

Accessible

Food is produced close to consumption centers, so transport and storage are reduced.

Products is fresher and taste is improved.

Healthy

The confined environment removes pests and pests, so no pesticides are needed.

Accurate control of nutrients and light improves quality.

Re-elaborated from “Introducing Healthy Vertical Farming”, https://news.Samsung.com/

Phytochemicals

Minerals

Land

Storage

Transport

H_2O

Environmental impact?

Energy?

Water use efficiency

How much food per water used?

Water use efficiency (WUE) of selected food products in response to the cropping system (*Source: Orsini et al., 2020, Sustainable use of resources in indoor farms with artificial lighting. European Journal of Horticultural Sciences, in press*).

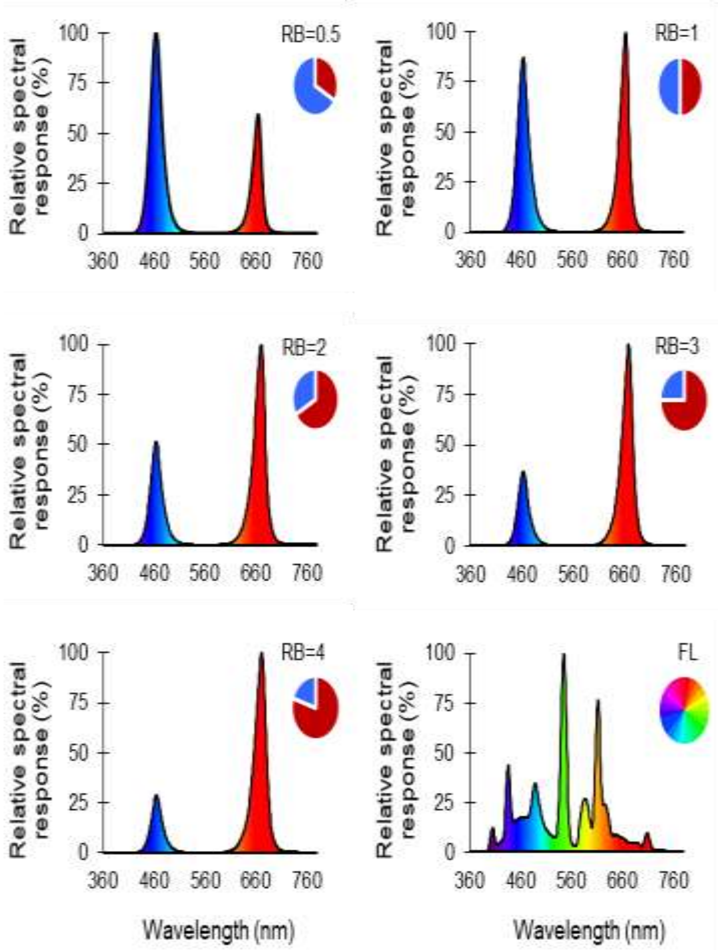
Water Use Efficiency

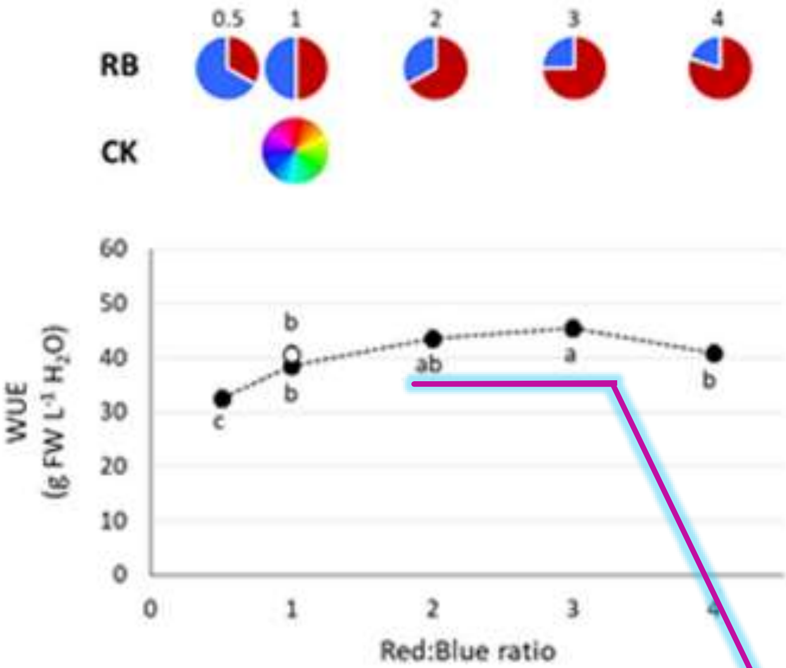
g FW L^{-1} H_2O

	Field	Greenhouse	PFAL
Lettuce	3-20	5-60	45-80
Basil	2-11	20-22	33-44
Rocket	5-8	5-15	18-26
Chicory	2-22	24-26	20-26

Milk	0.98-1.60
Egg	0.31-0.50
Chicken meat	0.23-0.27
Beef	0.04-0.06

Water use efficient LED spectrum

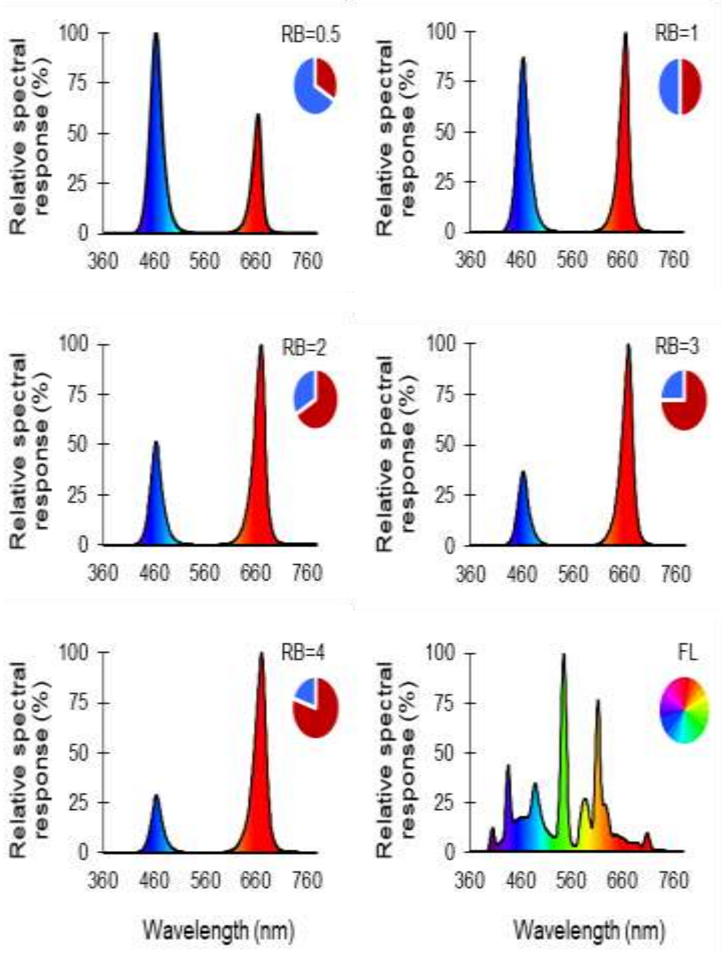


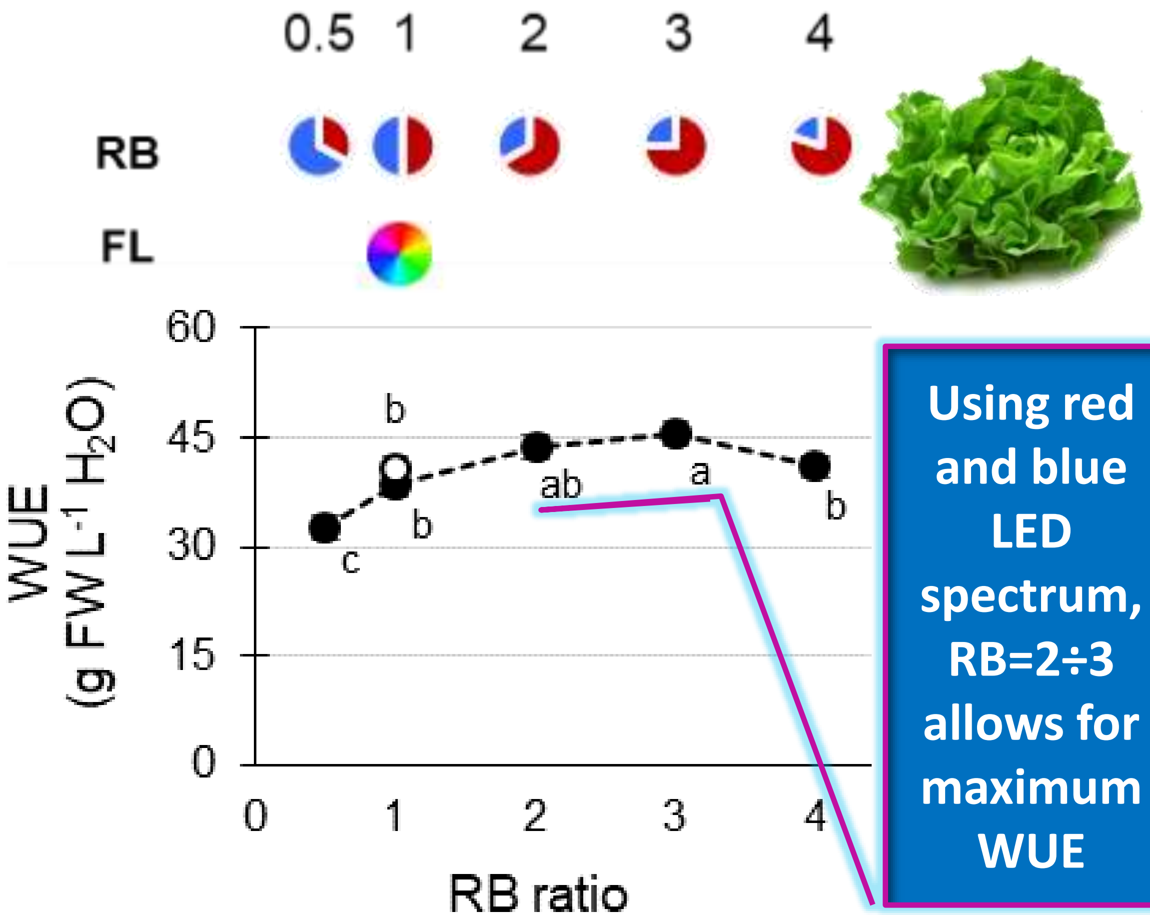


Using red and blue LED spectrum, RB=2÷3 allows for maximum WUE

Pennisi, G., Blasioli, S., Cellini, A., Maia, L., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernández, J.A., Stanghellini, C., Marcelis, L.F., Orsini, F., Gianquinto, G. 2019. Unravelling the role of red:blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science, doi: 10.3389/fpls.2019.00305

Water use efficient LED spectrum





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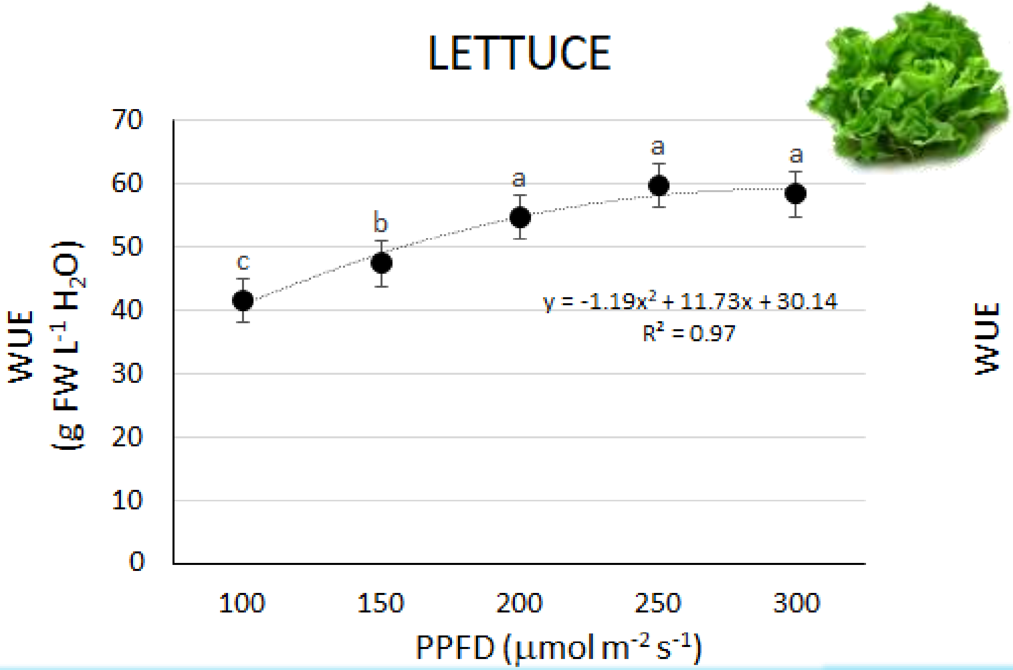
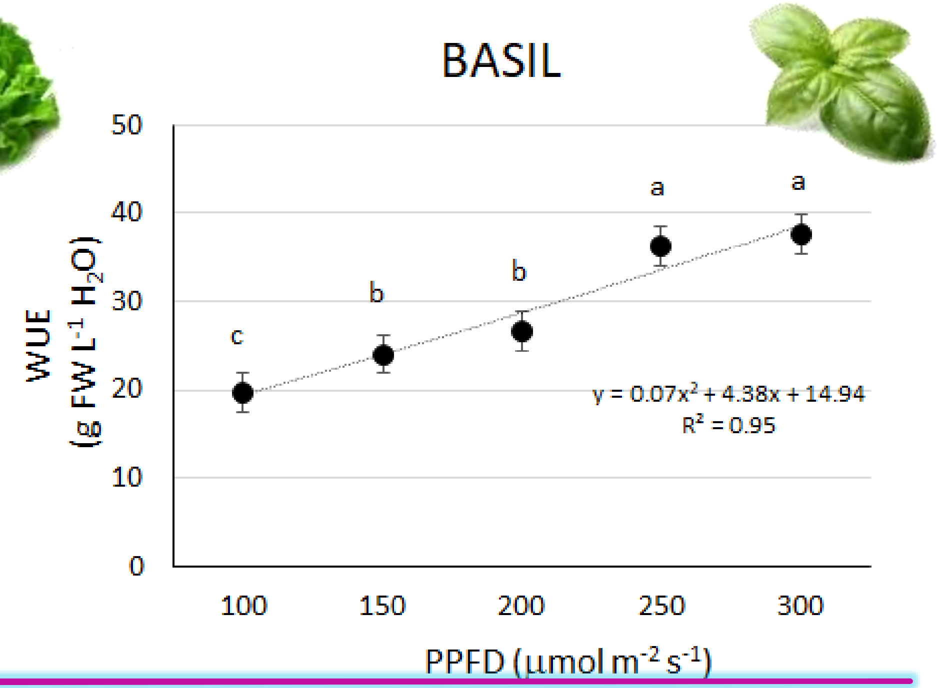
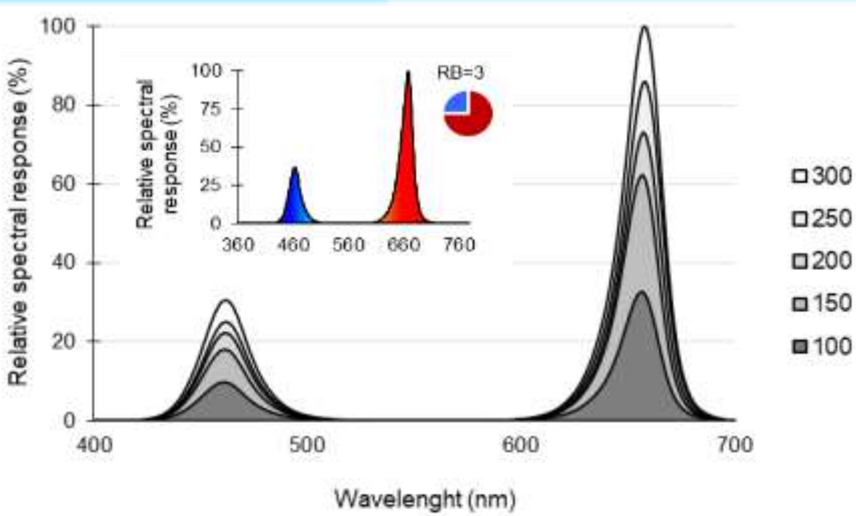
Water use efficient PPFD







Maximum WUE at PPFD≥200 μmol m^{-2} s^{-1} in lettuce and PPFD≥250 μmol m^{-2} s^{-1} in basil.

Pennisi et al., 2020. Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. Scientia Horticulturae, 272, 109508.

Transpiration water recovery

Experimental data on water use for 14 days in a Plant Factory with Artificial Lighting (RH=80%, air temperature 30 °C).

Dehumidified (76%)

Ventilated (7%)

Irrigated and humidified (100%)

Increase in plants and substrates (17%)

Re-elaborated from Kozai, 2015, building on data from Ohyama et al. (2000).

Land surface use efficiency

New ways for plant growing in PFALs

SUE (kg FW m^{-2} y^{-1})	Soil	Vertical tower
Lettuce:	11.2	28.3 (2.5x)
Kale:	7.2	21.6 (3.0x)
Spinach:	4.5	12.6 (2.8x)
Chrysanthemum:	5.3	14.2 (2.7x)

In greenhouses (from Liu et al. 2004)

Horizontal	Vertical
138	95
g FW $plant^{-1}$	g FW $plant^{-1}$

In PFALs (Touliatos et al. 2016)

Touliatos, Dodd and McAinsh, 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and Energy Security, 5: 184-191. Liu, Chen, and Liu, 2005. High efficiency column culture system in China. Acta Hortic. 691, 495-500

Surface needed to obtain 1 kg of fresh lettuce per day

Open field: 93 m^2

Greenhouse: 9 m^2

PFAL: 0.3 m^2

SUE (g FW m^{-2} d^{-1})

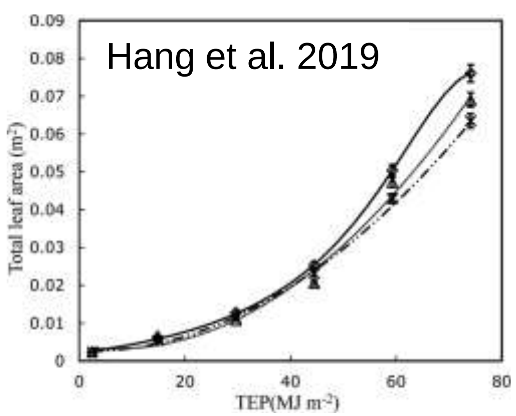
Open field	Greenhouse	10 layers PFAL
10	112	3110

Barbosa, G. et al. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. Int. J. Environ. Res. Public Health 12, 6879–6891Pennisi et al., 2019.
Pennisi, G., et al. 2019. Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red:blue ratio provided by LED lighting. NATURE Scientific Reports.

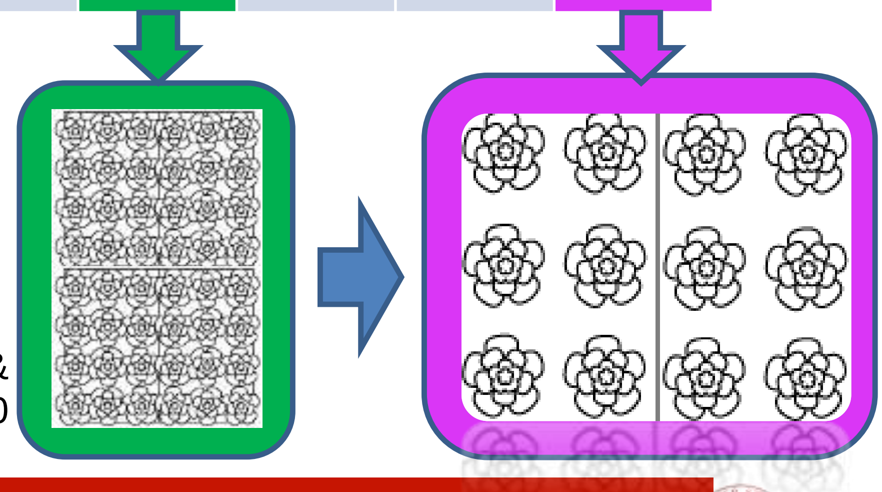
Adaptive plant spacing

Lettuce, optimal LAI=3 (Ohyama et al., 2000).

	Unit	Light integral (MJ m^{-2})			
		20	40	60	80
Leaf area	(m^2)	0.01	0.02	0.05	0.08
Optimal plant density	(plants m^{-2})	300	150	60	37.5

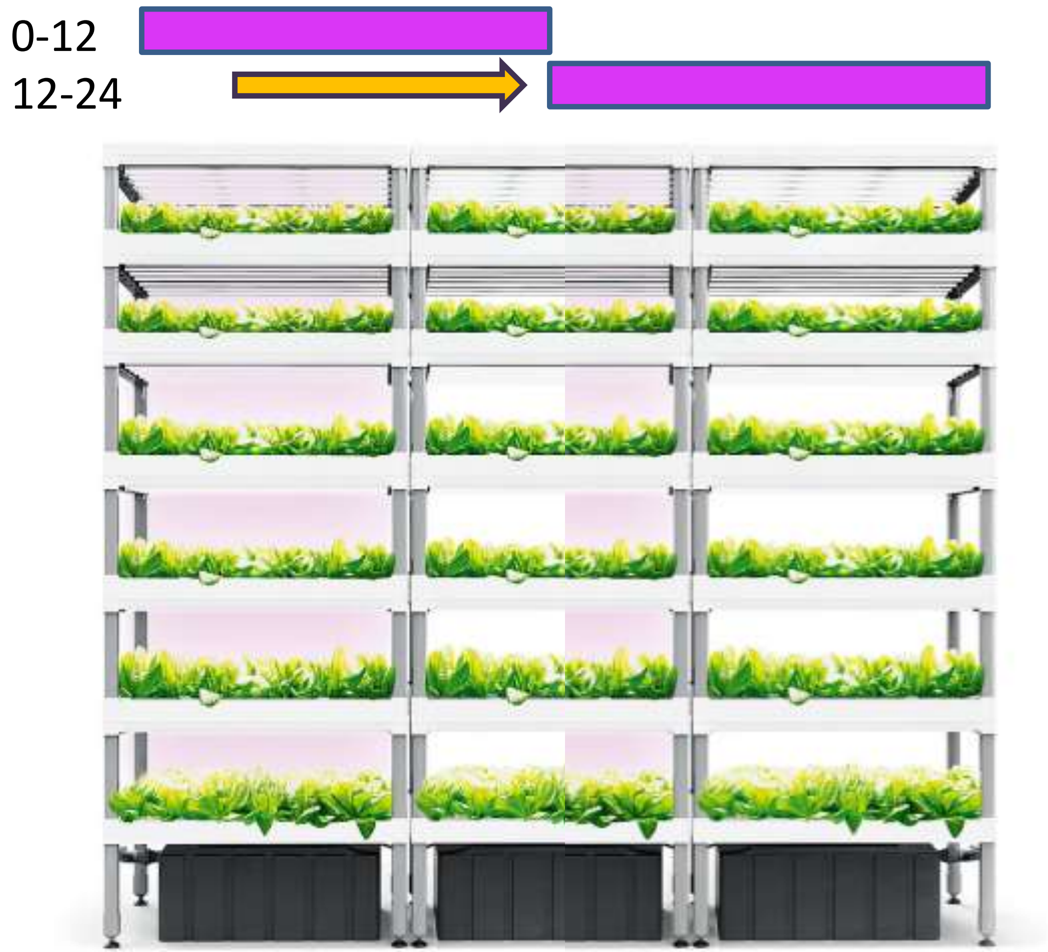


Ioslovich & Gutman. 2000



Ioslovich & Gutman. 2000. Optimal control of crop spacing in a plant factory. Automatica, 36(11), 1665-1668. Ohyama *et al.* 2000. Energy and mass balance of a closed-type transplant production system. Water balance. J. SHITA 12(4), 217–224. Hang et al. 2019. Leaf area model based on thermal effectiveness and photosynthetically active radiation in lettuce grown in mini-plant factories under different light cycles. Scientia Horticulturae, 252, 113-120.

Movable LED lamps



By adopting movable LED lamps it was possible to halve the cost of lamps per unit of growing surface based.

Li, K., Yang, Q. C., Tong, Y. X., & Cheng, R. (2014). Using movable light-emitting diodes for electricity savings in a plant factory growing lettuce. Horttechnology, 24(5), 546-553.

How much food per land used?

Land Surface Use Efficiency (SUE) of selected food products in response to the cropping system (*Source: Orsini et al., 2020, Sustainable use of resources in indoor farms with artificial lighting. European Journal of Horticultural Sciences, in press*).

Land Surface Use Efficiency

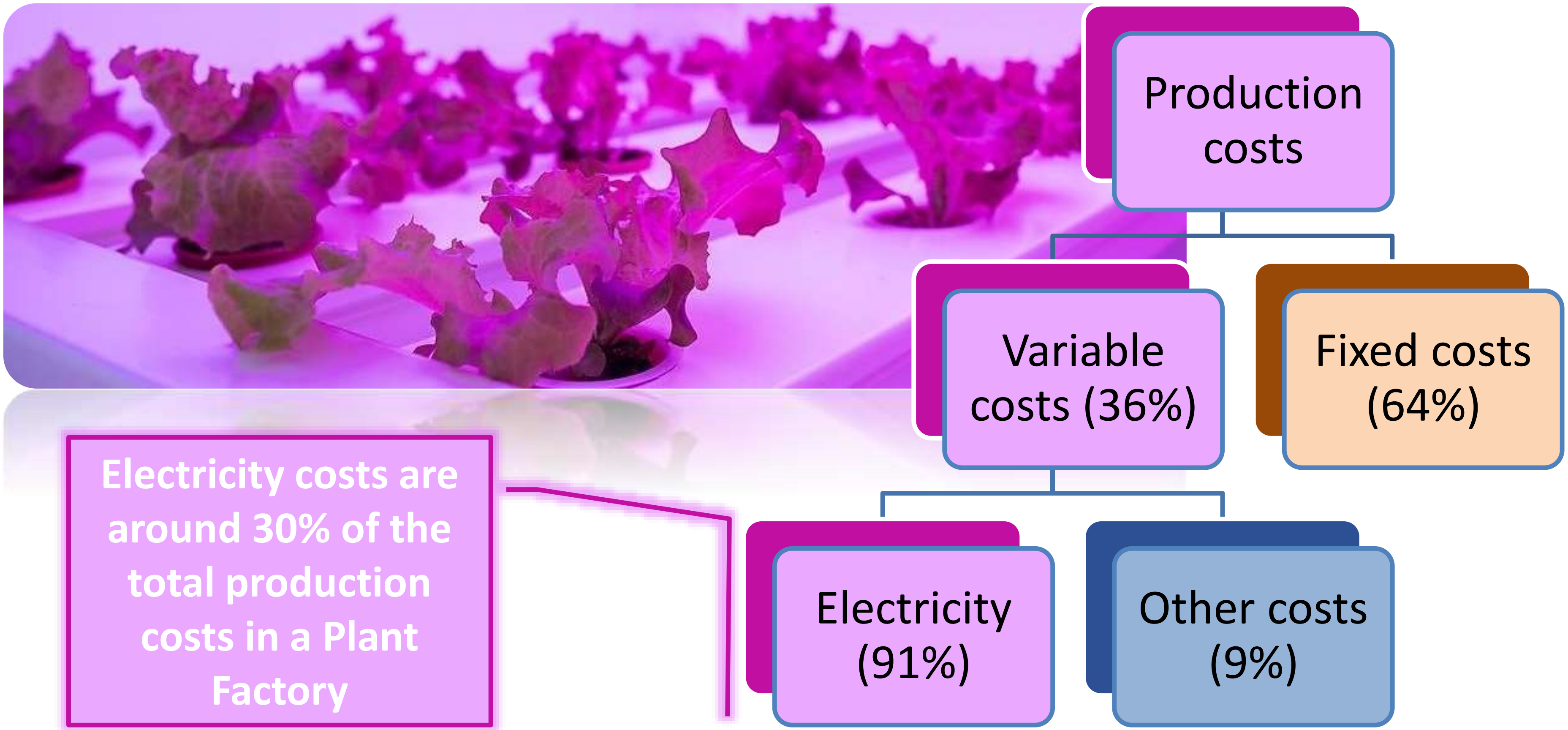
g FW m^{-2} d^{-1}

	Field	Greenhouse	PFAL
Lettuce	10 - 15	100 - 300	1300 - 3000
Basil	2 - 40	70 - 150	700 - 1500
Rocket	10 - 50	5 - 180	1000-1500
Chicory	5 - 30	5 - 300	700-1100

Milk	2.19
Egg	1.05
Chicken meat	0.85
Beef	0.06-0.16

Energy use efficiency

Energetic costs in plant factories



Yokoyama, R. Energy Consumption and Heat Sources in Plant Factories. In Yokoyama, R. (2019). Energy Consumption and Heat Sources in Plant Factories. In Plant Factory Using Artificial Light (pp. 177-184). Elsevier.

Electricity costs in plant factories

Electricity costs

- Light (50-55%)
- Climate control (30-35%)
- Production facilities (10-15%)

Electricity requirements for climate control are also dependent on the lamps efficiency (and their effect on the climate)

Yokoyama, R. Energy Consumption and Heat Sources in Plant Factories. In Yokoyama, R. (2019). Energy Consumption and Heat Sources in Plant Factories. In Plant Factory Using Artificial Light (pp. 177-184). Elsevier.

Energy consumption in a PFAL

Data from Experimental Plant Factory at Osaka Prefecture University.

Lettuce production of 5’000 plants per day.

	Annual energy consumption (MWh year-1)	Relative consumption (%)	Energy consumption per head of lettuce (kWh)
LED light	1’906	52.7%	1.044
Air Conditioning by heat pumps	1’232	34.1%	0.675
Production facilities	478	13.2%	0.262
Total	3’616		1.981

~ 0.20 Euro kWh^{-1} (in Italy)

~ 0.40 Euro $head^{-1}$

T. Ogura, T. Wada, Elemental systems and consideration points for the design of a plant factory, Air-Cond. Sanit. Eng. 89 (5) (2015) 35–41 (in Japanese).

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Improving energy use efficiency by means of climate control systems

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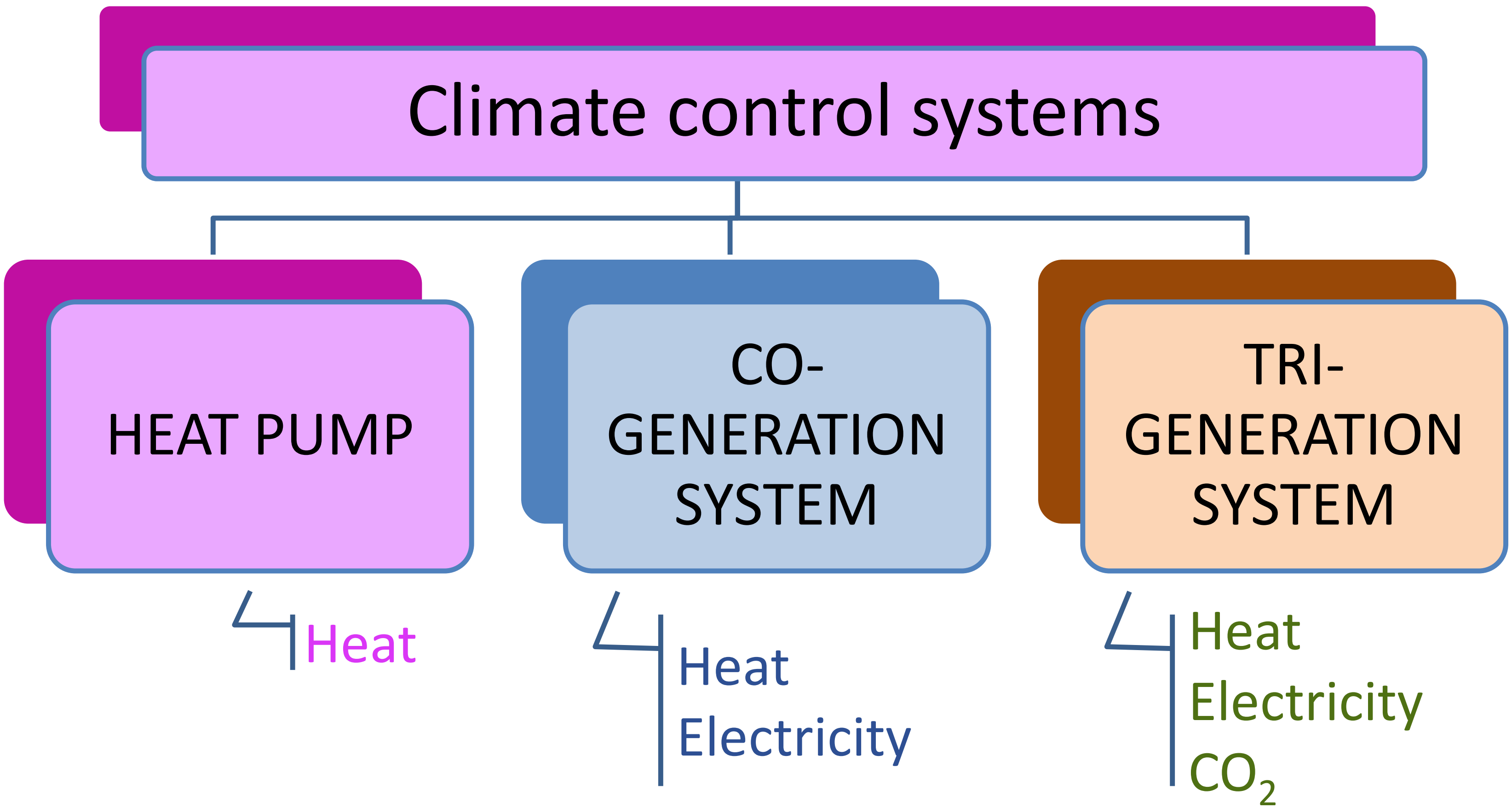
Climate control systems



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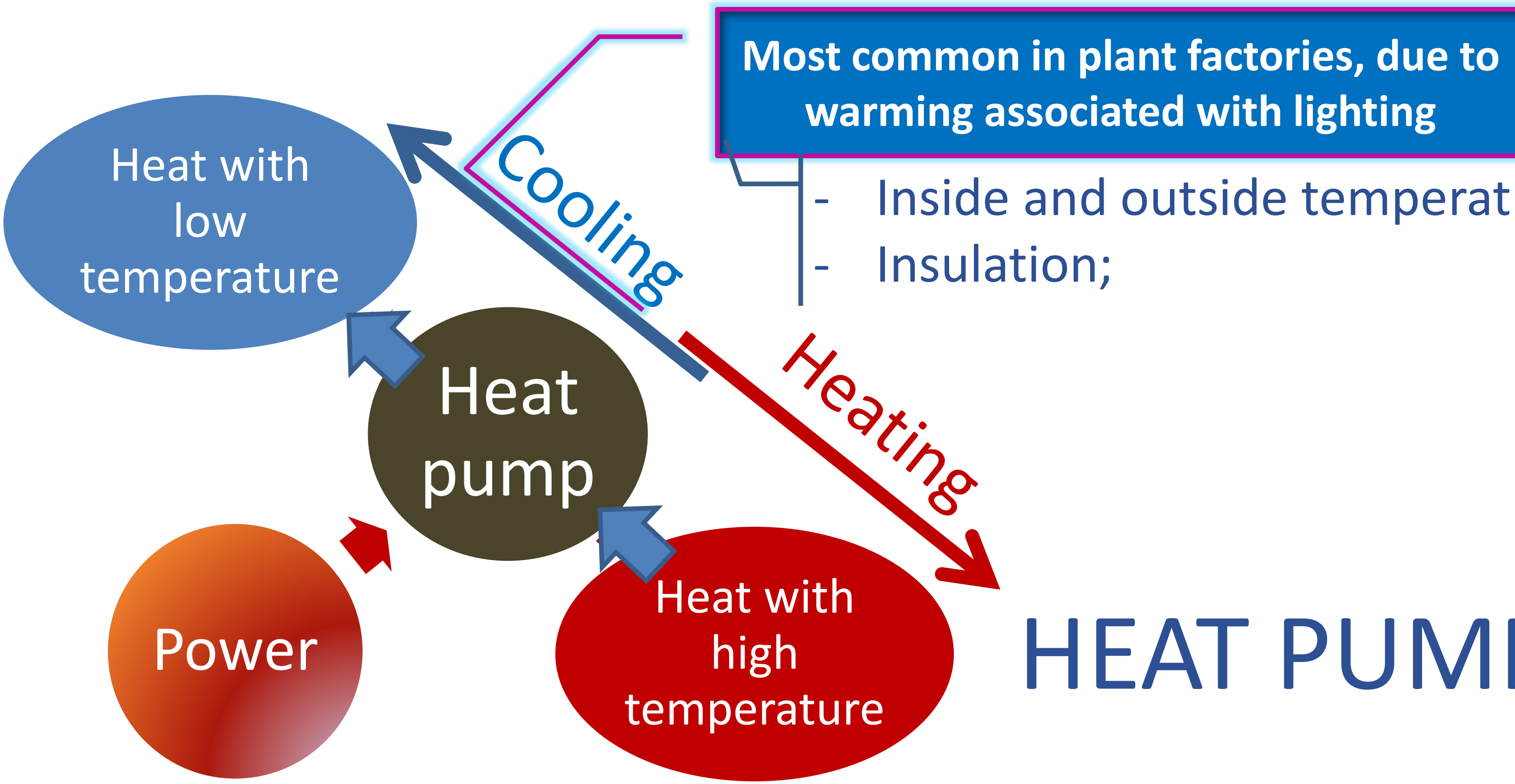
Climate control systems

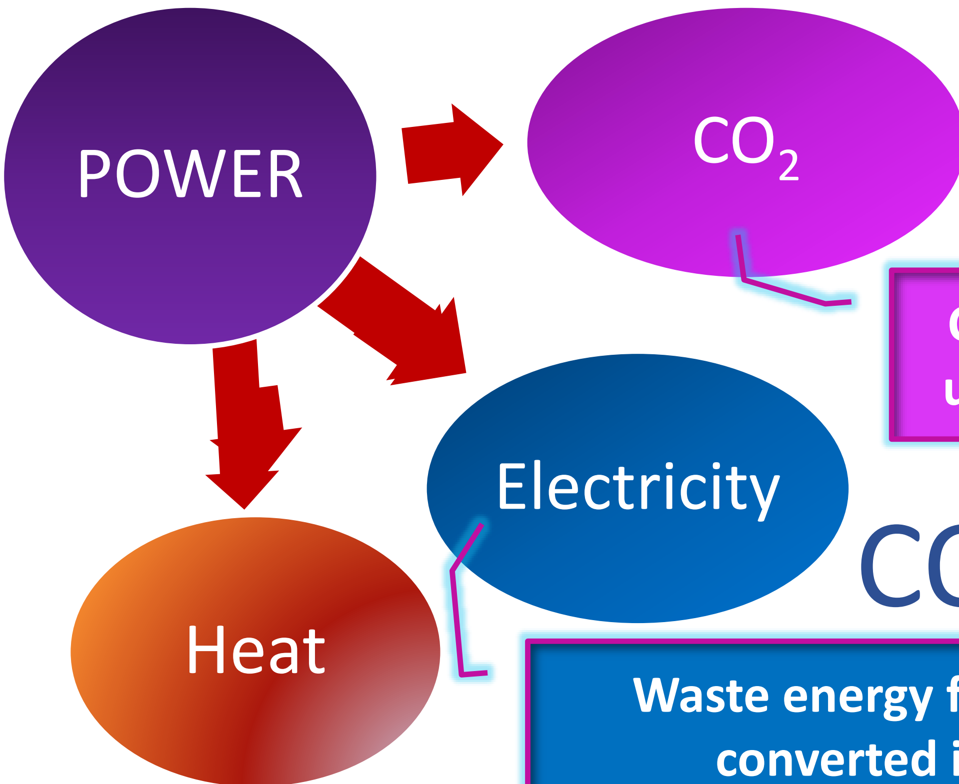


- Inside and outside temperature;
- Insulation;

HEAT PUMPS

Yokoyama, R. Energy Consumption and Heat Sources in Plant Factories. In Yokoyama, R. (2019). Energy Consumption and Heat Sources in Plant Factories. In Plant Factory Using Artificial Light (pp. 177-184). Elsevier.

Climate control systems



TRI-GENERATION

CO_2 **produced by combustion may be used to promote crop photosynthesis**

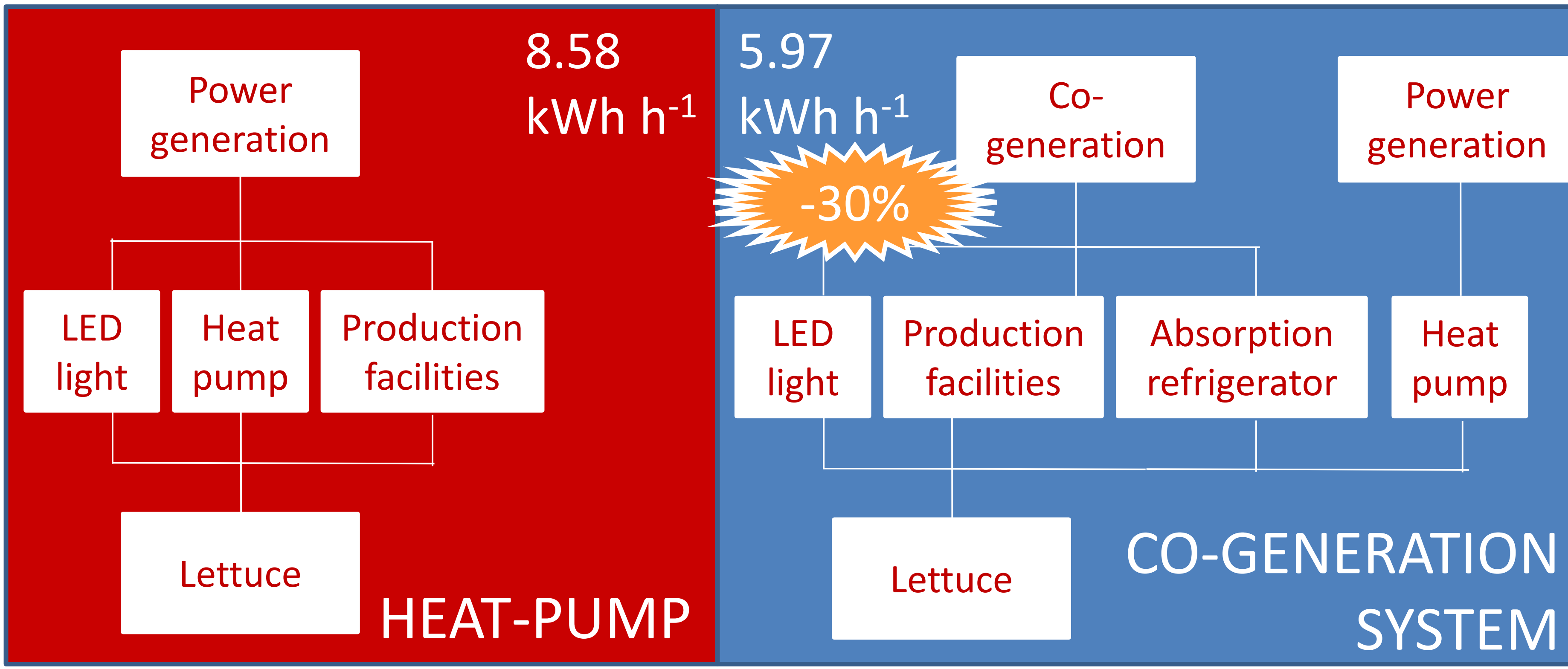
CO-GENERATION

Waste energy from the system is converted into electricity

Yokoyama, R. Energy Consumption and Heat Sources in Plant Factories. In Yokoyama, R. (2019). Energy Consumption and Heat Sources in Plant Factories. In Plant Factory Using Artificial Light (pp. 177-184). Elsevier.

Heat pump or Co-generation?

Model data from Experimental Plant Factory at Osaka Prefecture University. Lettuce production of 5’000 plants per day.



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Improving energy use efficiency by means of light management

Efficacy of the diodes to convert electricity into photons

	PPE ($\mu mol\ J^{-1}$)	
RED diode	2.3	2.6
BLUE diode	1.8	2.0
	Park and Runkle, 2018	Blanken et al., 2013

More photons are released by LEDs emitting at longer wavelengths

BUT…

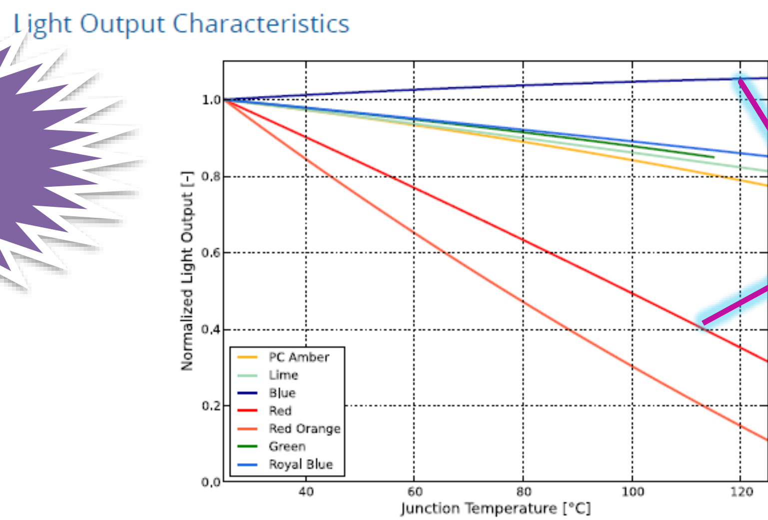

Figure 2. Typical normalized light output vs. junction temperature for LUXEON 3535L Color Line at 100mA.

In response to increasing junction temperature, BLUE diodes may increase their efficacy while RED diodes decrease it (Wang et al., 2007; Pennisi et al., 2019)

Pennisi et al., 2019 Unravelling the role of red:blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science. Wang et al., 2007. Effects of using light-emitting diodes on the cultivation of Spirulina platensis. Biochem. Eng. J. 37, 21–25. Park and Runkle 2018. Spectral effects of light-emitting diodes on plant growth, visual color quality, and photosynthetic photon efficacy: white versus blue plus red radiation. PLoS One 13:e0202386. Blanken et al., 2013. Cultivation of microalgae on artificial light comes at a cost. Algal Res. 2, 333–340.

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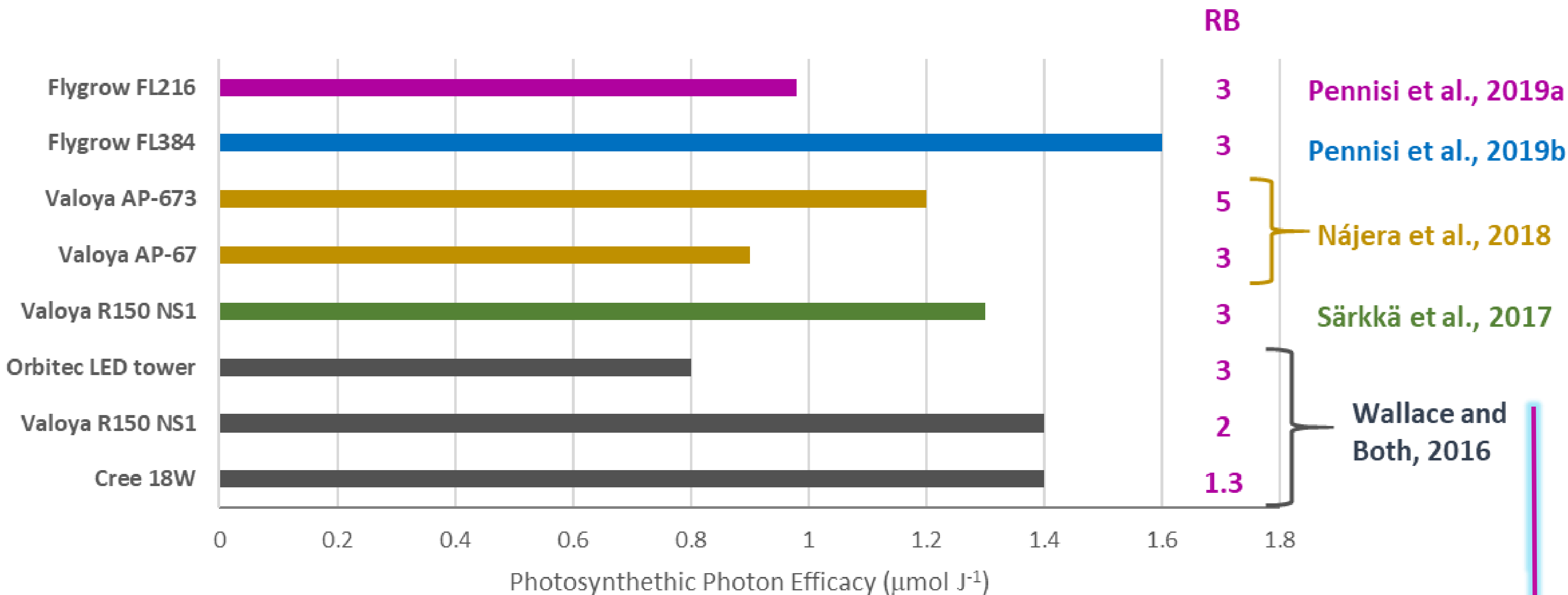
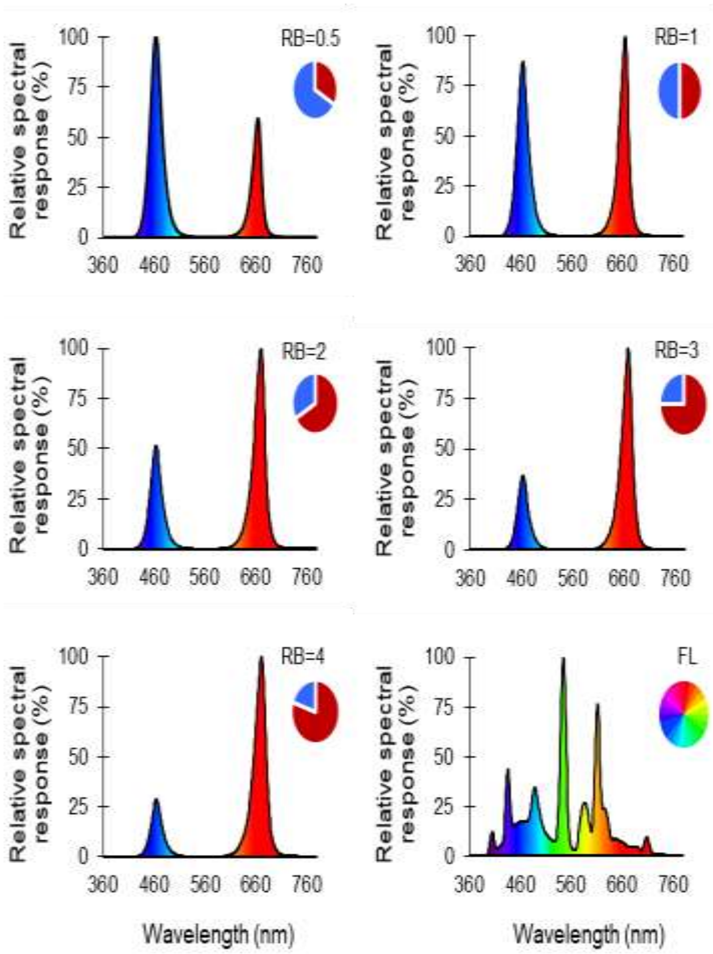
Efficacy of lamps to convert electricity into light photons

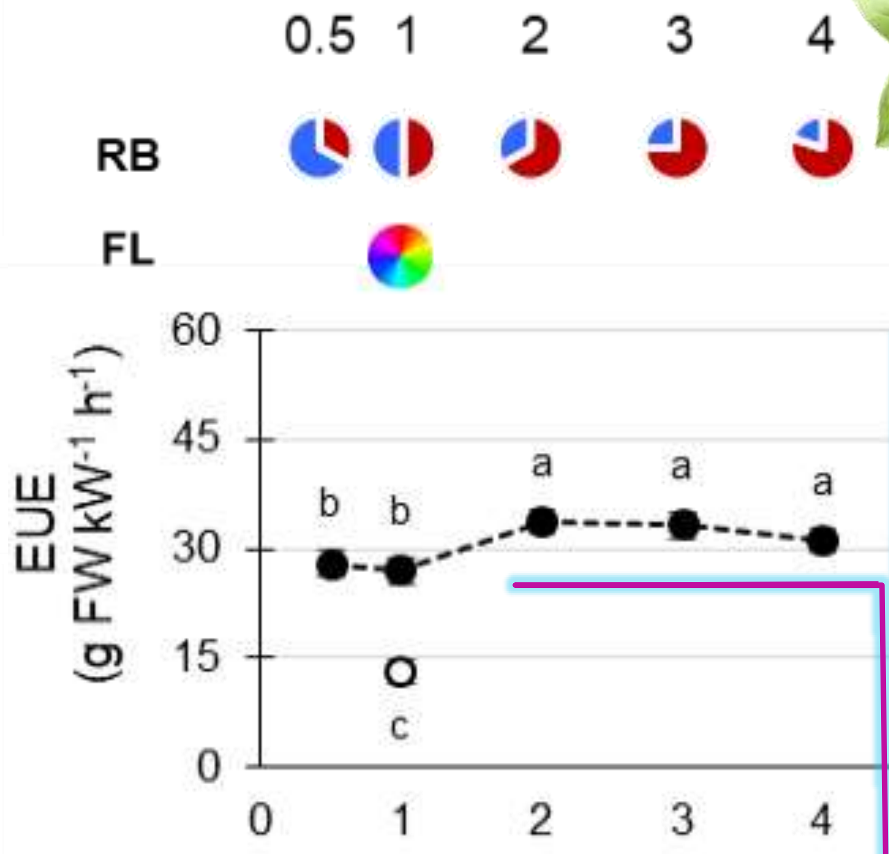


Photosynthetic Photon Efficacy depends on lamp features rather than RB ratio.

Pennisi et al., 2019a. Unravelling the role of red:blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science, in press. doi: 10.3389/fpls.2019.00305 Pennisi et al., 2019b. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability, 11(15), 4063. Nájera et al., 2018. LED-enhanced dietary and organoleptic qualities in postharvest tomato fruit. Postharv. Biol. Technol. 145, 151–156. Särkkä et al., 2017. Effects of HPS and LED lighting on cucumber leaf photosynthesis, light quality penetration and temperature in the canopy, plant morphology and yield. Agric. Food Sci. 26, 102–110. Wallace and Both 2016. Evaluating operating characteristics of light sources for horticultural applications. Acta Hortic. 1134, 435–444.

Energy use efficient LED spectrum

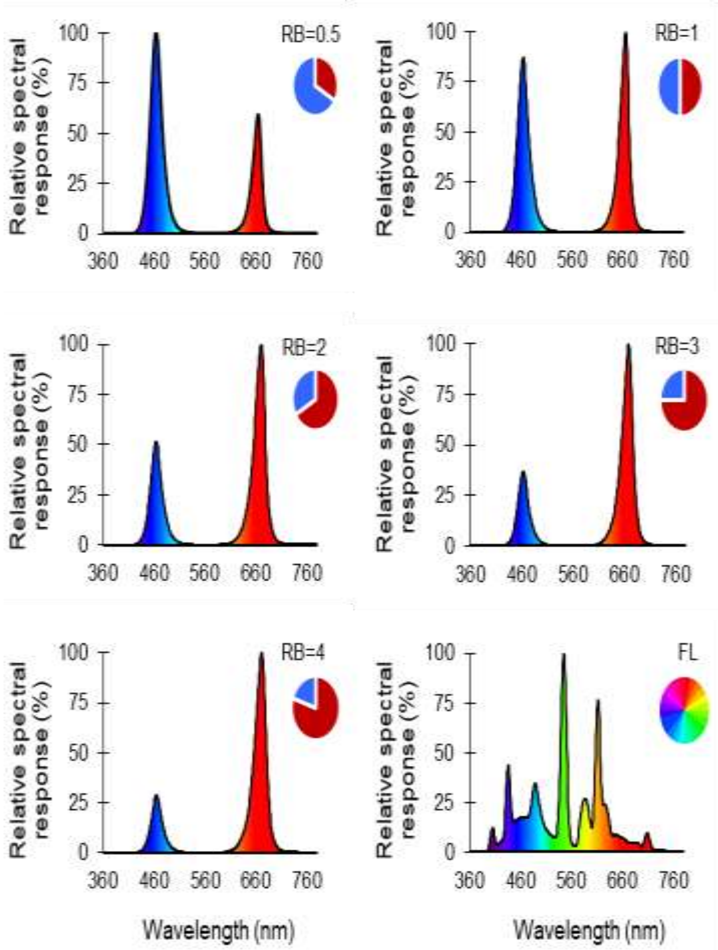


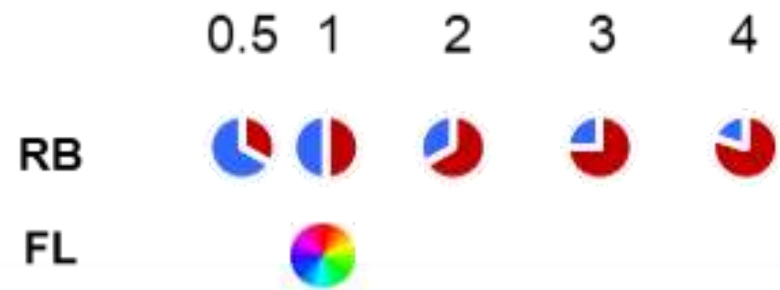


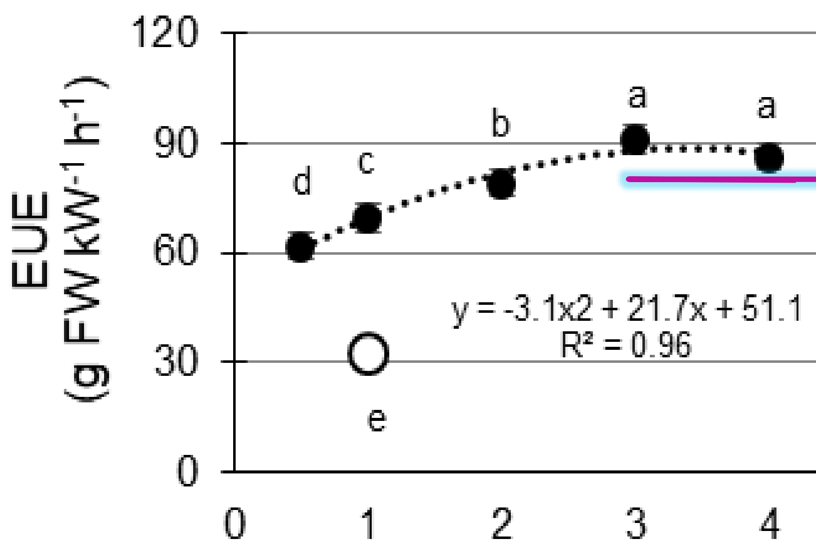
Using red and blue LED spectrum, RB≥2 allows for maximum EUE

Pennisi, G., Blasioli, S., Cellini, A., Maia, L., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernández, J.A., Stanghellini, C., Marcelis, L.F., Orsini, F., Gianquinto, G. 2019. Unravelling the role of red:blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science, doi: 10.3389/fpls.2019.00305

Energy use efficient LED spectrum







Using red and blue LED spectrum, RB≥3 allows for maximum EUE

Pennisi, G., Orsini, F., Blasioli, S., Cellini, A., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernández, J.A., Stanghellini, C., Gianquinto, G., Marcelis, L.F. 2019. Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red:blue ratio provided by LED lighting. NATURE Scientific Reports, 9, 14127

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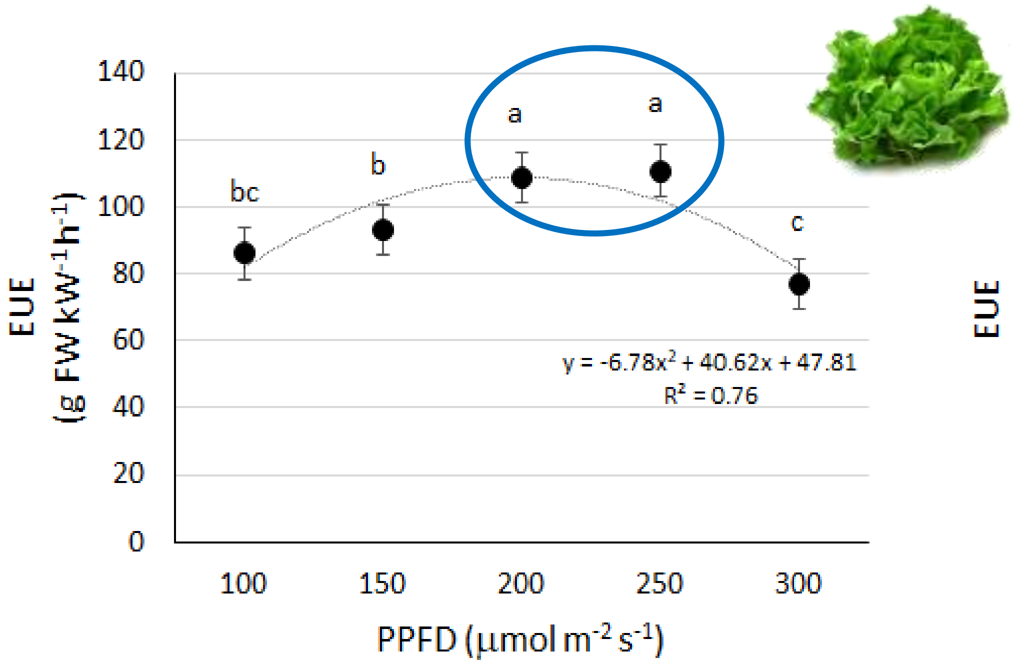
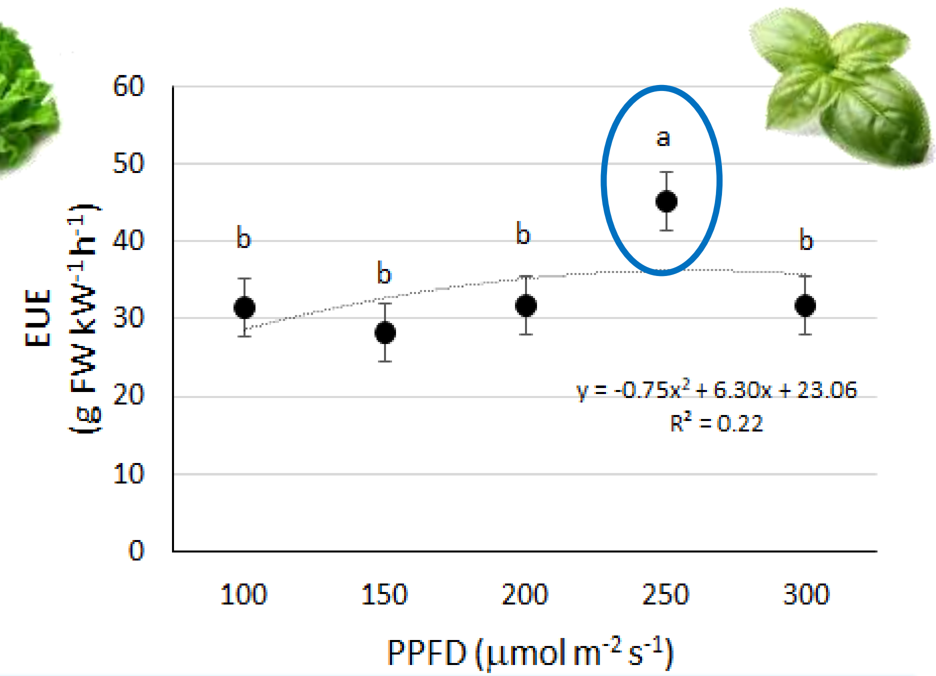
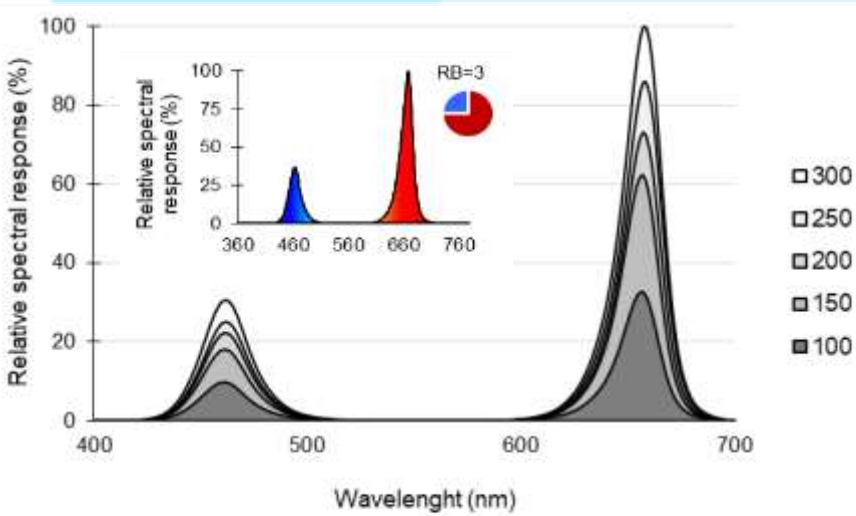
Energy use efficient PPFD



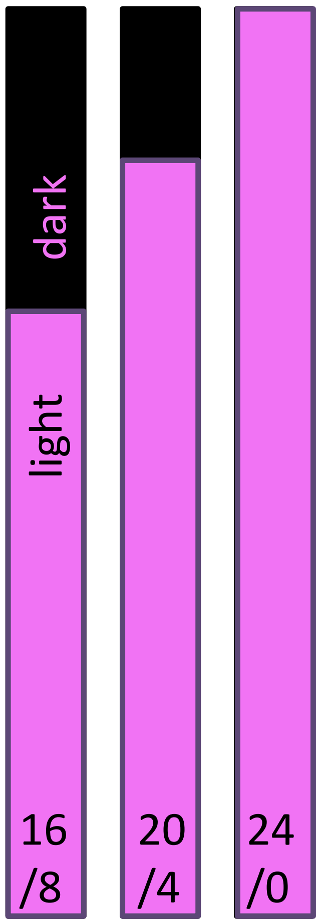


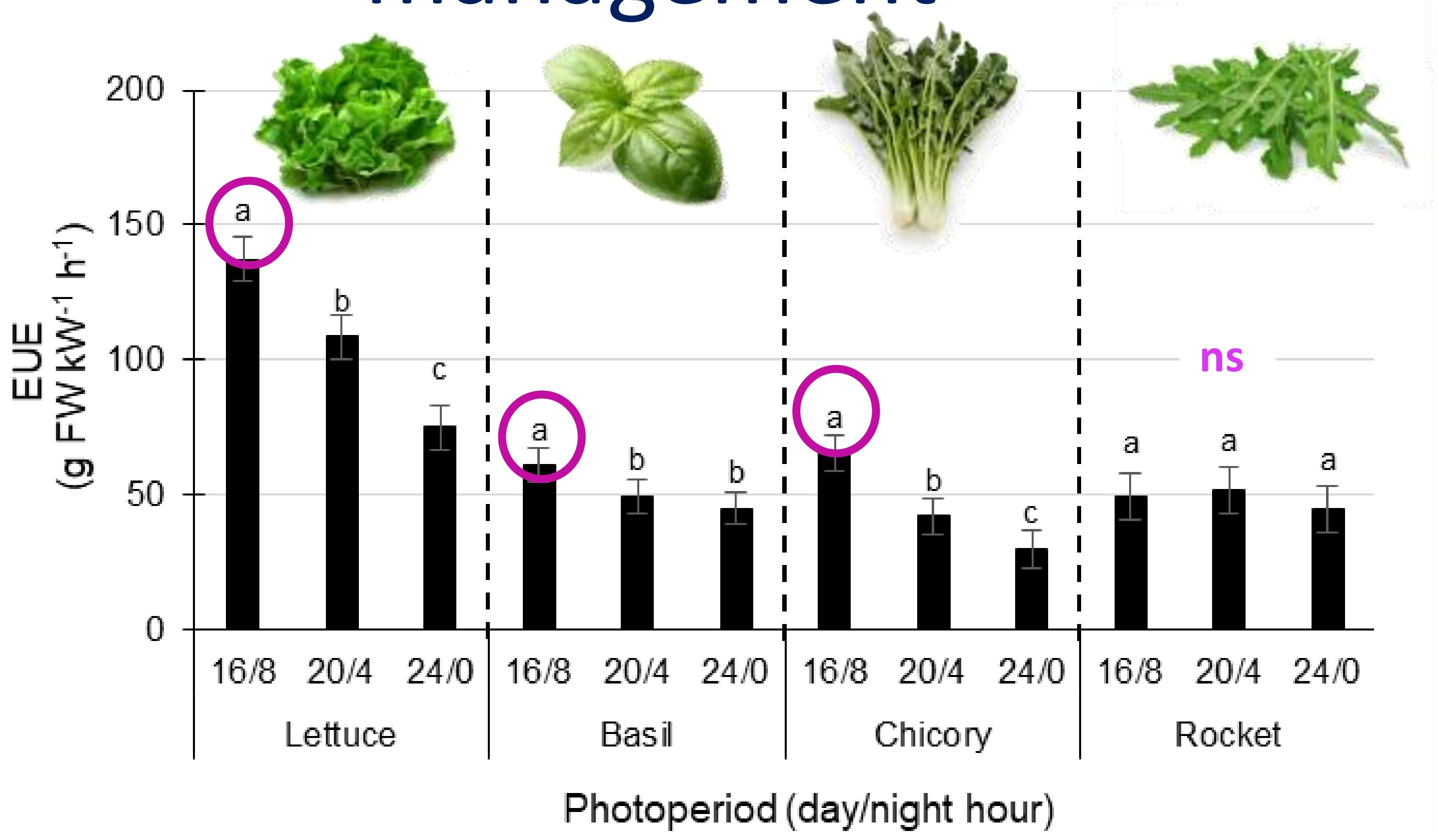


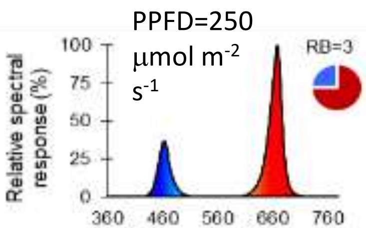
In lettuce maximum EUE at 200 and 250 µmol m^{-2} s^{-1}, in basil at 250 µmol m^{-2} s^{-1}.

Pennisi et al., 2020. Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. Scientia Horticulturae, 272, 109508.

Energy use efficient photoperiod management







In lettuce, basil and chicory maximum EUE at 16/8 hours of photoperiod. In rocket EUE is not affected by photoperiod.

Pennisi et al., 2020. Optimal photoperiod for indoor cultivation of leafy vegetables and herbs. European Journal of Horticultural Sciences, in press.

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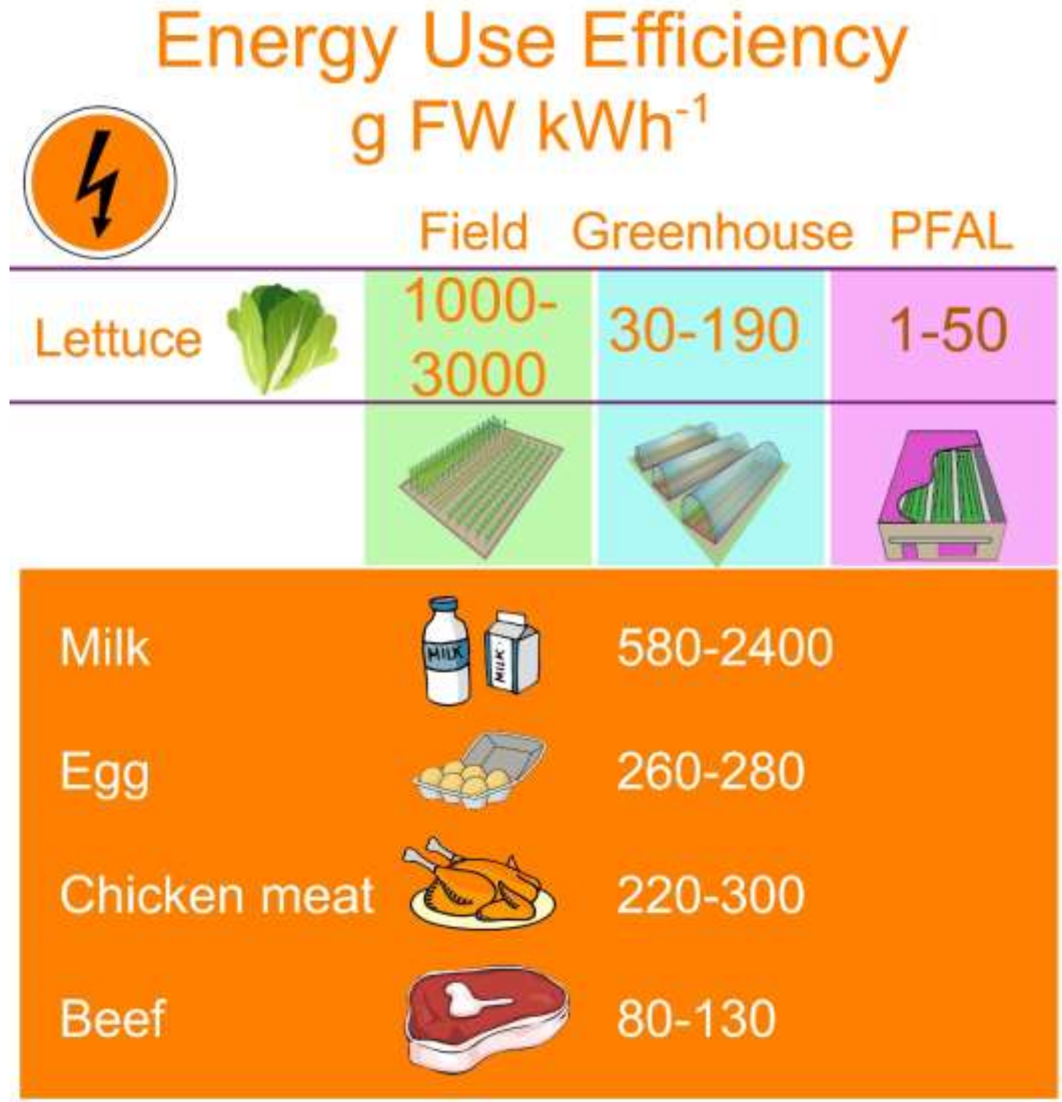
How much food per energy used?



Energy Use Efficiency (EUE) of selected food products in response to the cropping system (*Source: Orsini et al., 2020, Sustainable use of resources in indoor farms with artificial lighting. European Journal of Horticultural Sciences, in press*).

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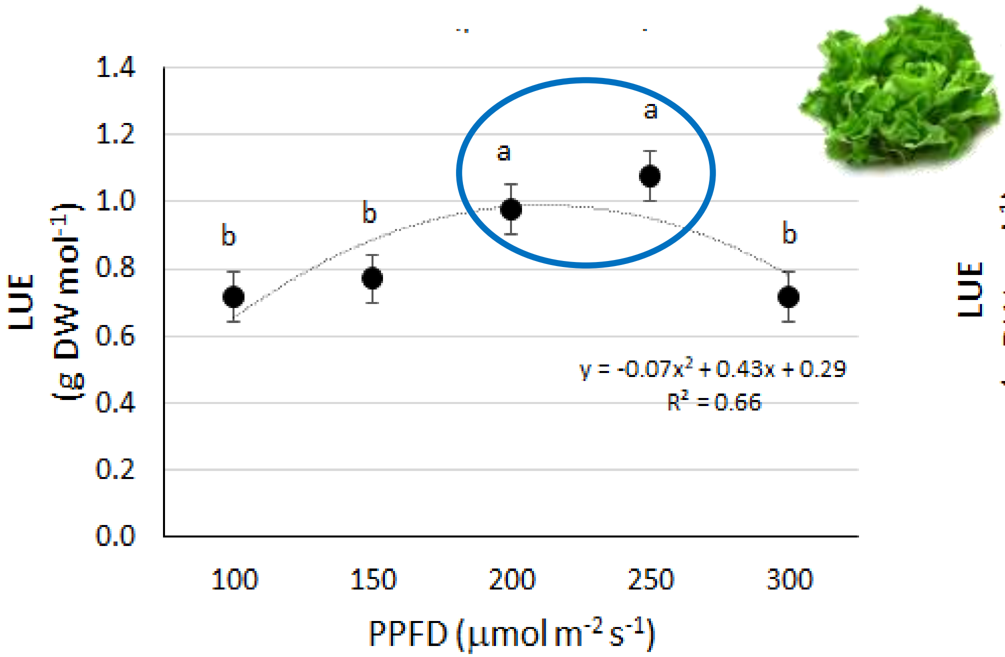
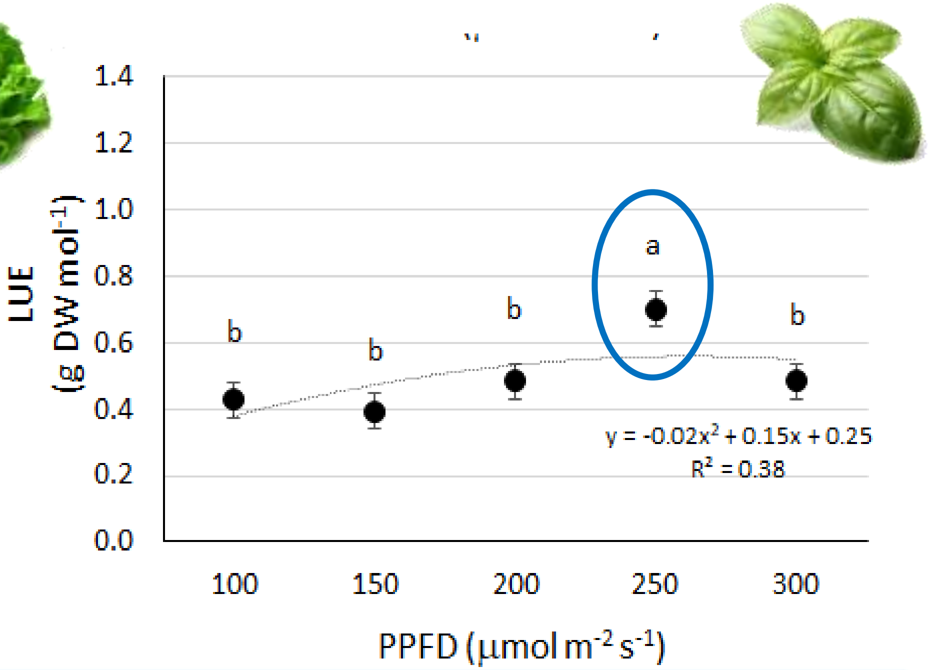
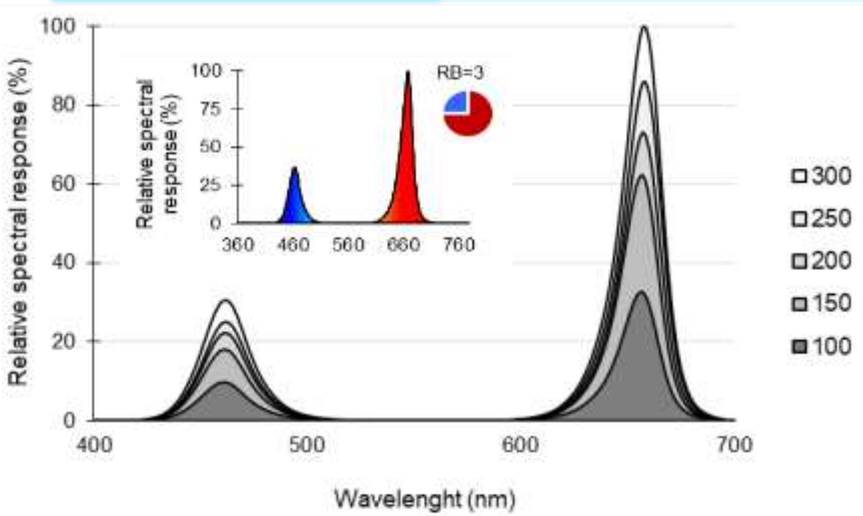
Light use efficiency

Light use efficient PPFD



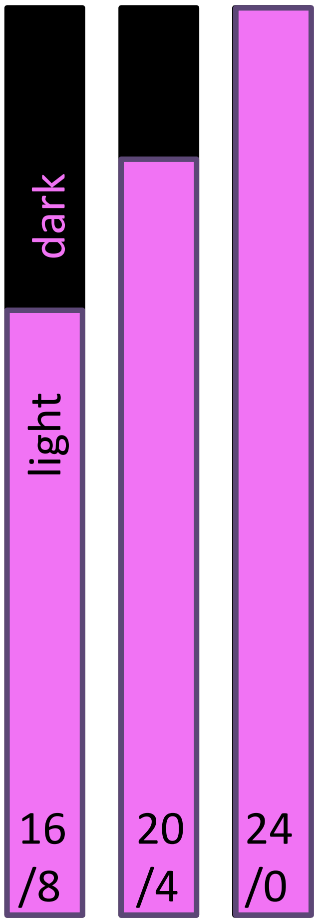


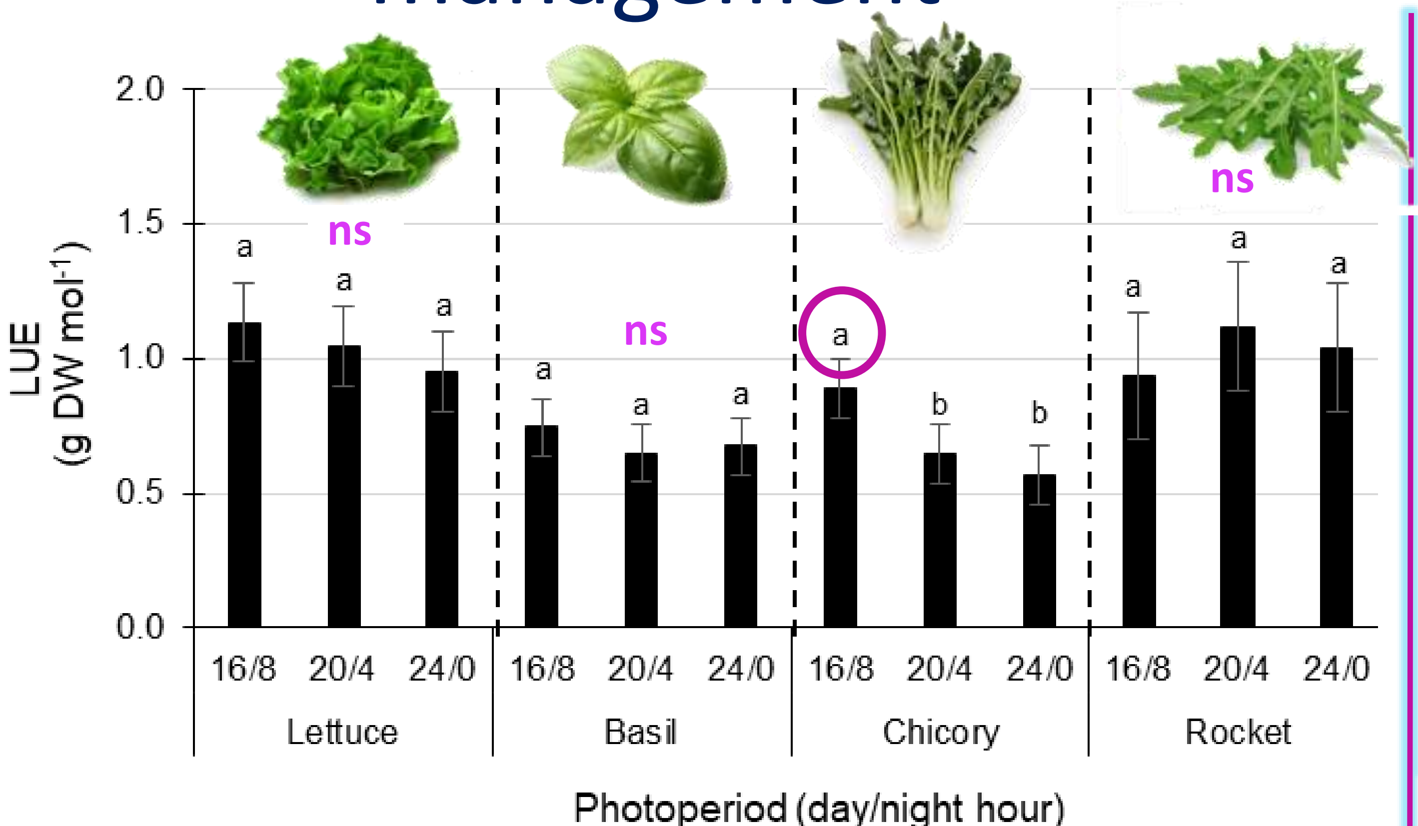


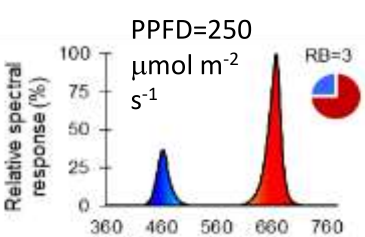
In lettuce maximum LUE at 200 and 250 µmol m^{-2} s^{-1}, in basil at 250 µmol m^{-2} s^{-1}.

Pennisi et al., 2020. Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. Scientia Horticulturae, 272, 109508.

Light use efficient photoperiod management







In chicory maximum LUE at 16/8 hours of photoperiod. In lettuce, basil and rocket EUE is not affected by photoperiod.

Pennisi et al., 2020. Optimal photoperiod for indoor cultivation of leafy vegetables and herbs. European Journal of Horticultural Sciences, in press.

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Environmental assessment of indoor farms

Plant factory typologies

SunLight Based (PFSLs)

Artificial Light Based (PFALs)

Kikuchi et al., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186: 703-717

LCA studies based on plant factory typology (from SCOPUS database)

SunLight Based (PFSLs)

10 entries (keywords: LCA; greenhouse cultivation)

Artificial Light Based (PFALs)

4 entries (keywords: LCA; indoor farming; vertical farming; plant factories)

Sunlight based plant factories

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Environmental assessment studies of greenhouse crop production

A LCA-study on greenhouse technologies:

Greenhouse with zinc-coated steel structure and glass covering (Greenhouse “A”).

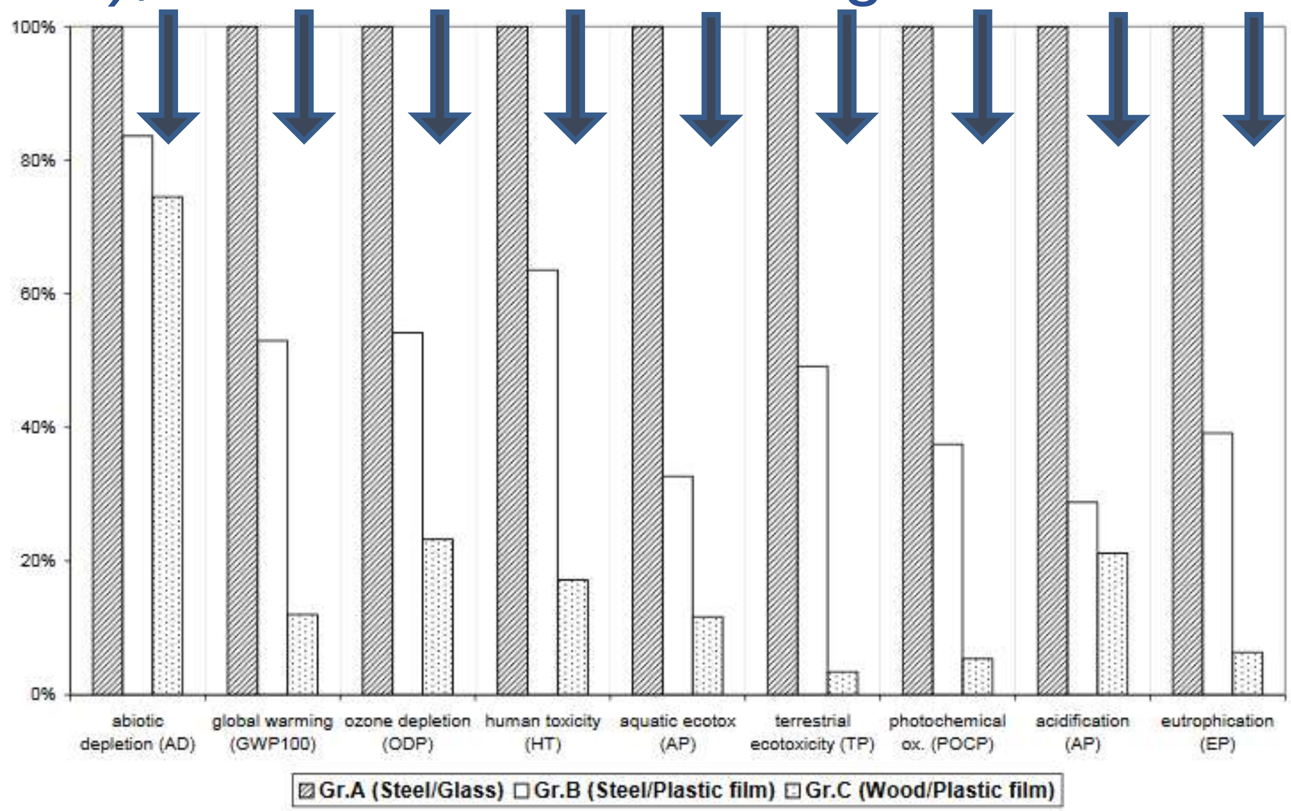
Tunnel shaped zinc-coated steel structure covered with an LDPE-based plastic film (Greenhouse “B”).

Greenhouse with Oakwood structure covered with an LDPE-based plastic film (Greenhouse “C”).

Russo, G. and Scarascia Mugnozza, G. (2005). LCA METHODOLOGY APPLIED TO VARIOUS TYPOLOGY OF GREENHOUSES. Acta Hortic. 691, 837-844 DOI: 10.17660/ActaHortic.2005.691.103

Environmental assessment studies of greenhouse crop production

Environmental impact is reduced using low tech systems (e.g. wood, plastic film), instead of steel and glass

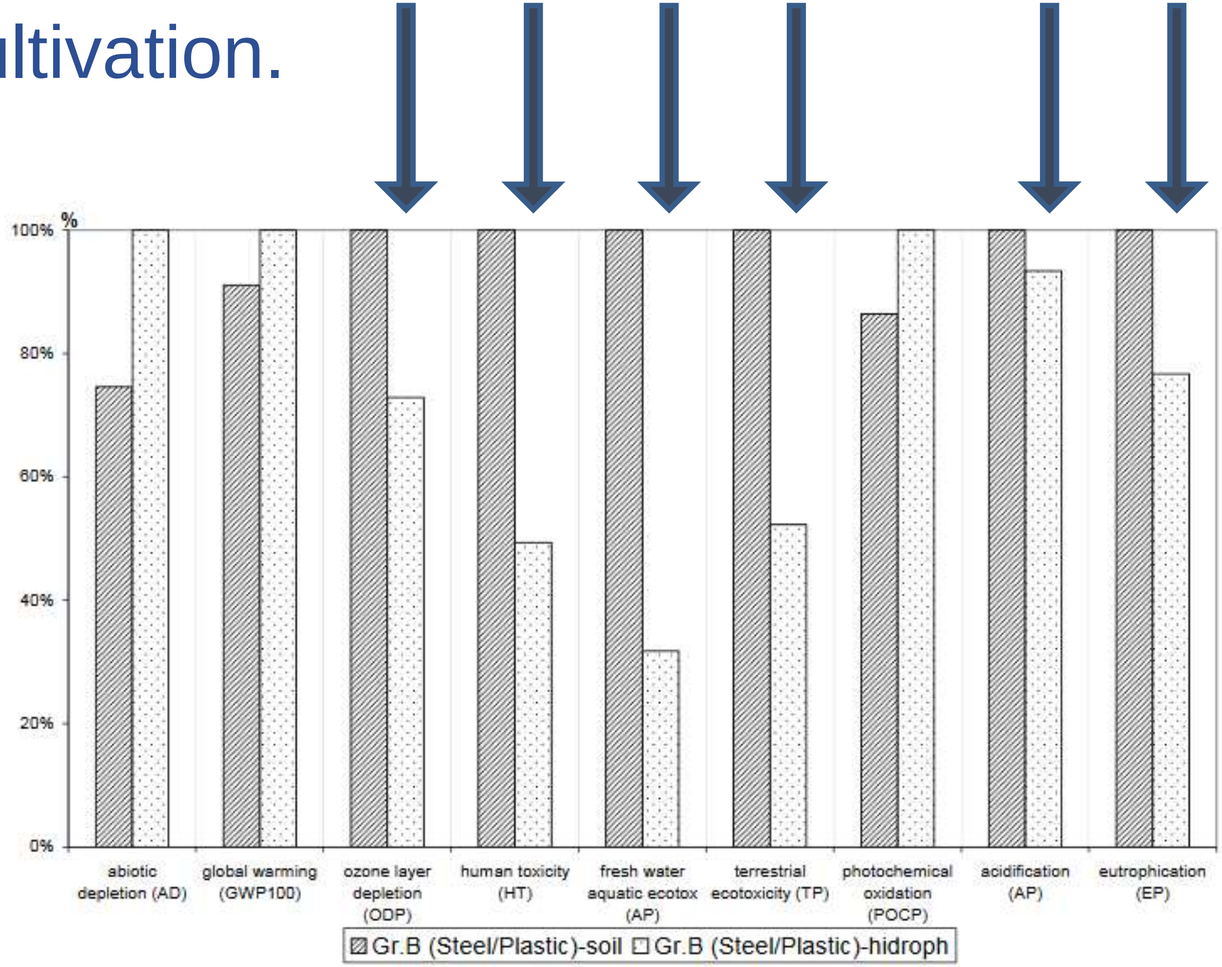


Russo, G. and Scarascia Mugnozza, G. (2005). LCA METHODOLOGY APPLIED TO VARIOUS TYPOLOGY OF GREENHOUSES. Acta Hortic. 691, 837-844 DOI: 10.17660/ActaHortic.2005.691.103

Environmental assessment studies of greenhouse crop production

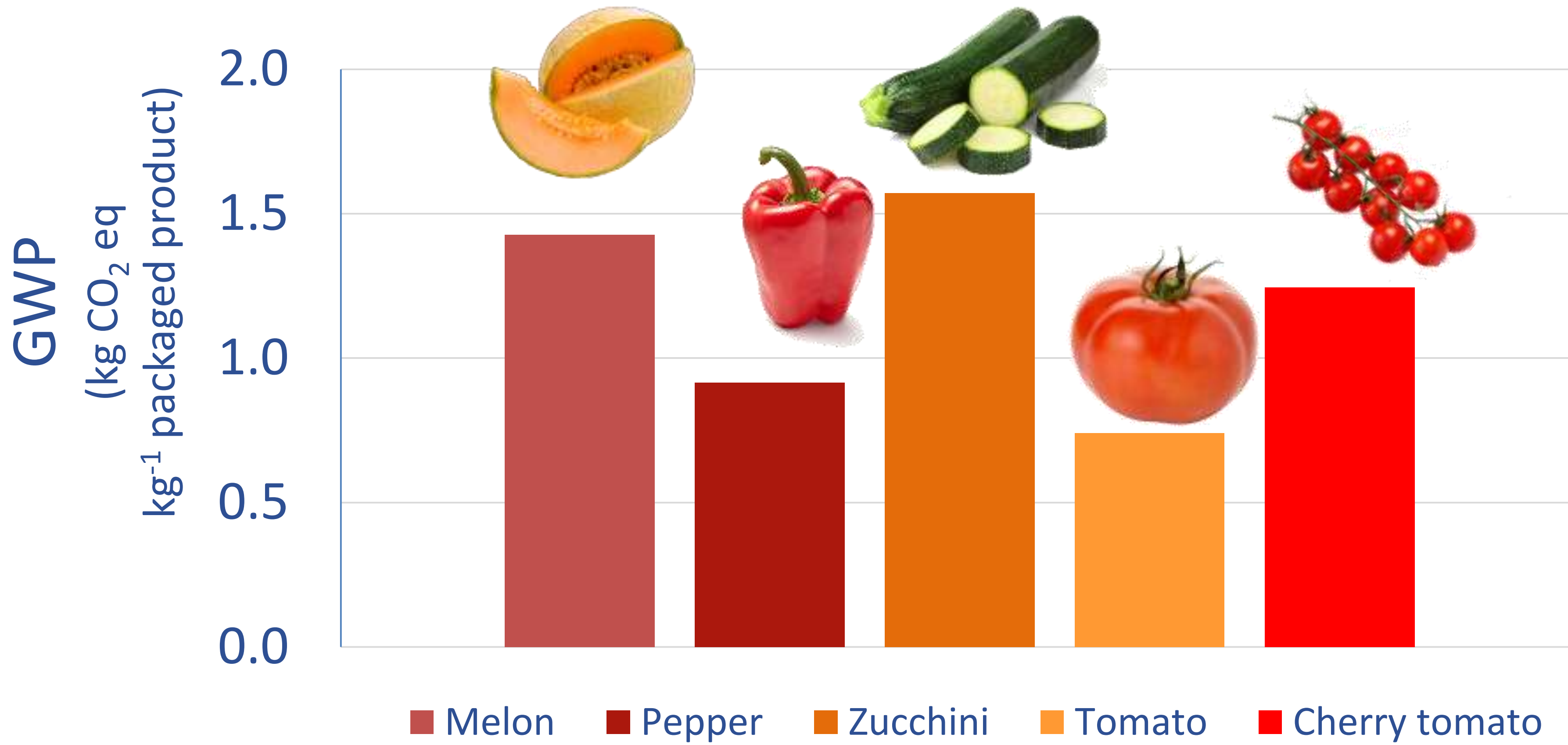
Environmental impact is reduced using hydroponics instead of on-soil cultivation.

Reduced environmental contamination and improved resource use efficiency



Russo, G. and Scarascia Mugnozza, G. (2005). LCA METHODOLOGY APPLIED TO VARIOUS TYPOLOGY OF GREENHOUSES. Acta Hortic. 691, 837-844 DOI: 10.17660/ActaHortic.2005.691.103

Environmental impact of greenhouse crops in Italy



Cellura, M., Longo, S., & Mistretta, M. (2012). Life Cycle Assessment (LCA) of protected crops: an Italian case study. Journal of cleaner production, 28, 56-62.

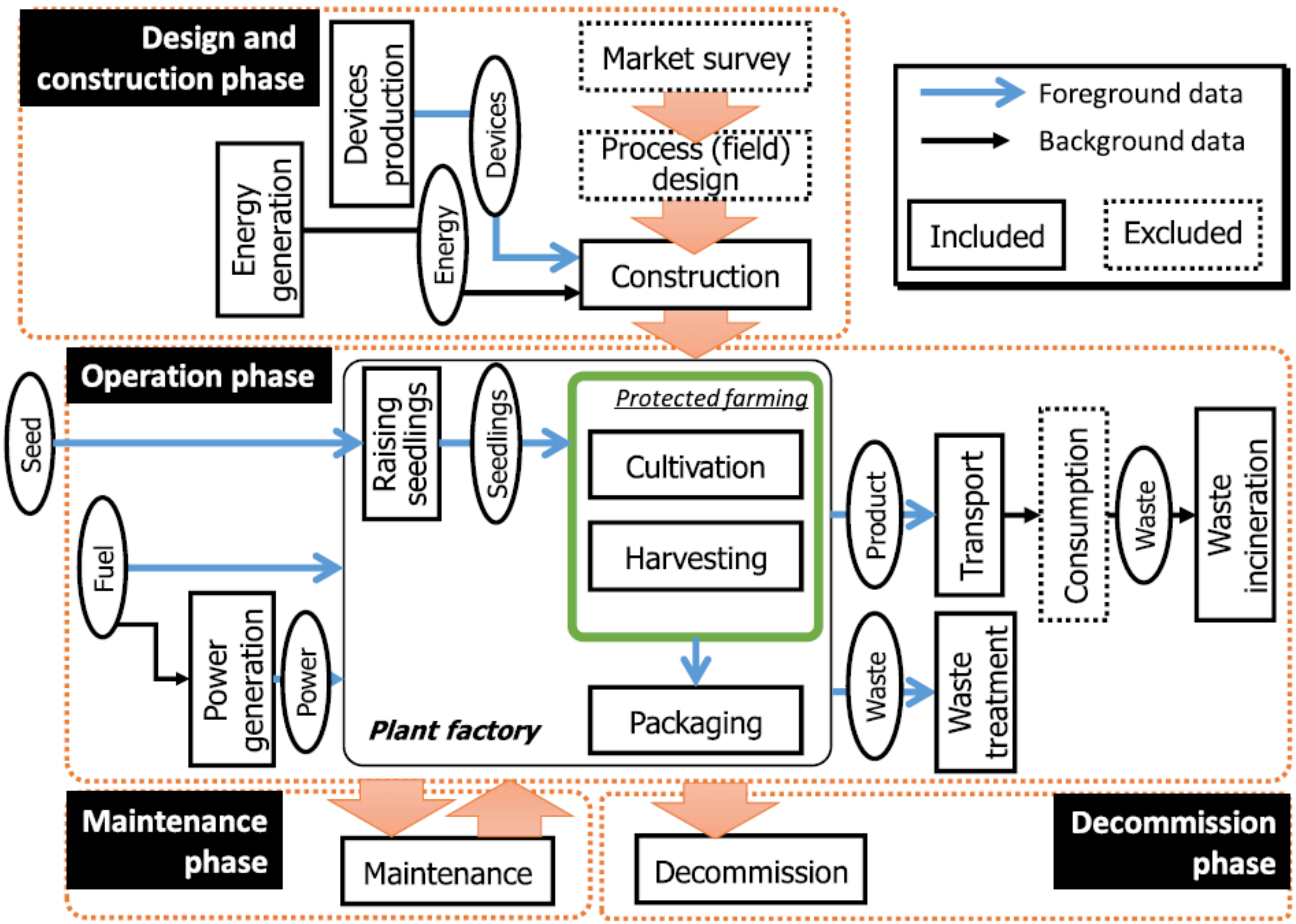
Plant Factories with artificial lighting

Environmental assessment of plant factories?

Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan

Kikuchi et al., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186: 703-717

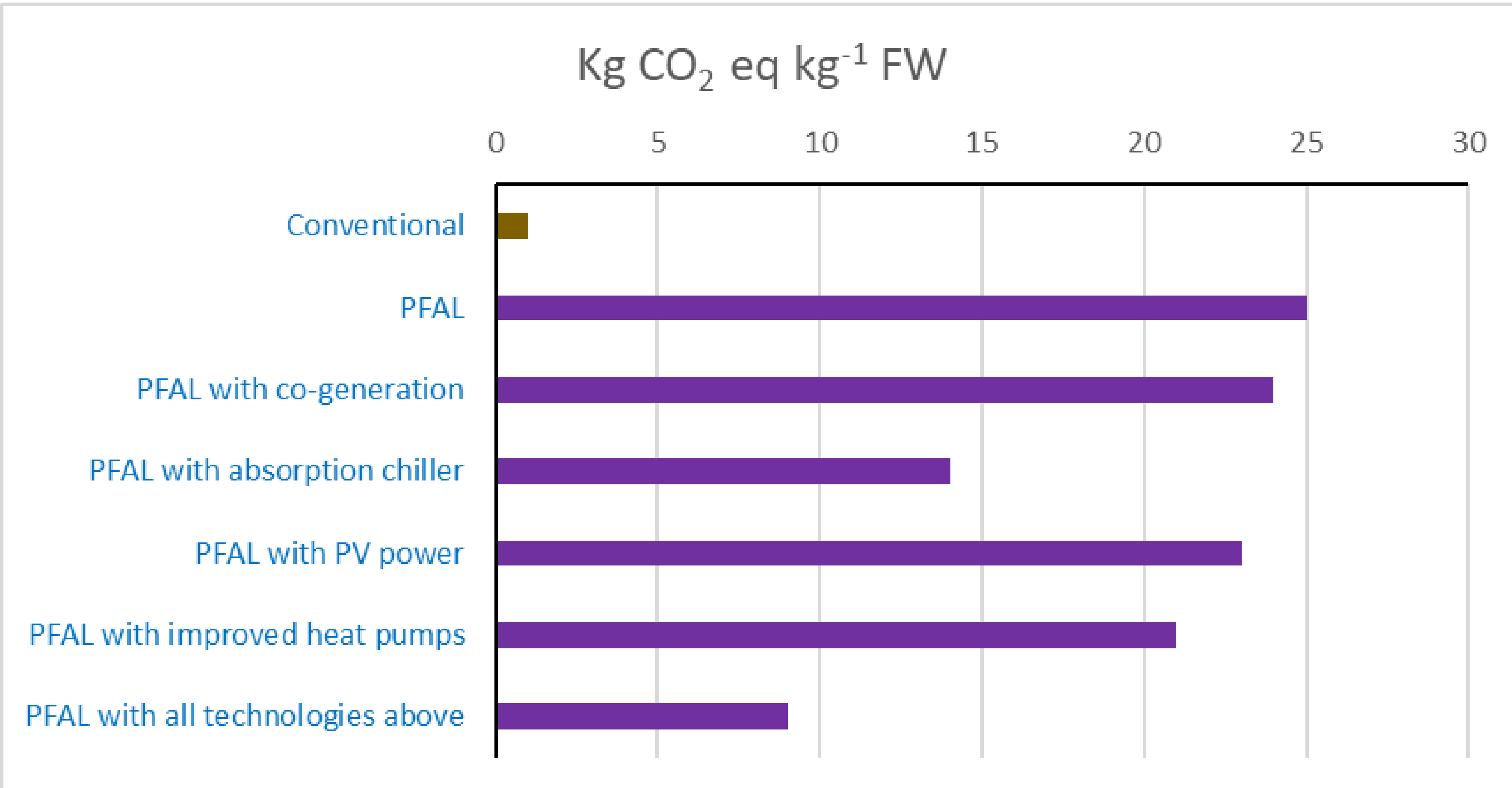
Boundaries of the LCA analysis



Comparison of scenarios at different technological level.

Kikuchi et al., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186: 703-717

Results of the LCA analysis



Kikuchi et al., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186: 703-717

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Are Plant Factories sustainable?

- Current plant factories reduce phosphorus, water, and land requirements for food production.
- Current plant factories cause higher greenhouse gas emissions than conventional systems.
  - Energy for plant factories can be saved by emerging energy technology options.
  - Solar-light plant factories are more efficient, but less widely applicable.
  - Artificial-light plant factories are comparatively less efficient, but widely applicable.

Kikuchi et al., 2018. Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186: 703-717

Plant factories vs Greenhouses

Graamans, L., Baeza, E., Van Den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems*, *160*, 31-43.

Agricultural Systems 160 (2018) 31–43

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Plant factories versus greenhouses: Comparison of resource use efficiency

Luuk Graamans[a,*], Esteban Baeza[b], Andy van den Dobbelsteen[a], Ilias Tsafaras[b], Cecilia Stanghellini[b]

[a] Delft University of Technology, Faculty of Architecture and the Built Environment, P.O. Box 5043, 2600 GA Delft, The Netherlands
[b] Wageningen University & Research, Unit Greenhouse Horticulture, P.O. Box 644, 6700 AP Wageningen, The Netherlands

Resource requirement in plant factories

- To quantify resource requirement for lettuce production in greenhouses and plant factories
- To analyse how this is affected by external climate.



The models

- Greenhouses: dynamic model KASPRO (De Zwart, 1996 and several additions)

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- Plant Factory:
  EnergyPlus + DesignBuilder

DesignBuilder

EnergyPlus

- Lettuce growth model (van Henten, 1994)

ELSEVIER

Agricultural Systems

Volume 45, Issue 1, 1994, Pages 55-72

Validation of a dynamic lettuce growth model for greenhouse climate control

E.J. Van Henten

Show more

https://doi.org/10.1016/S0308-521X(94)90280-1

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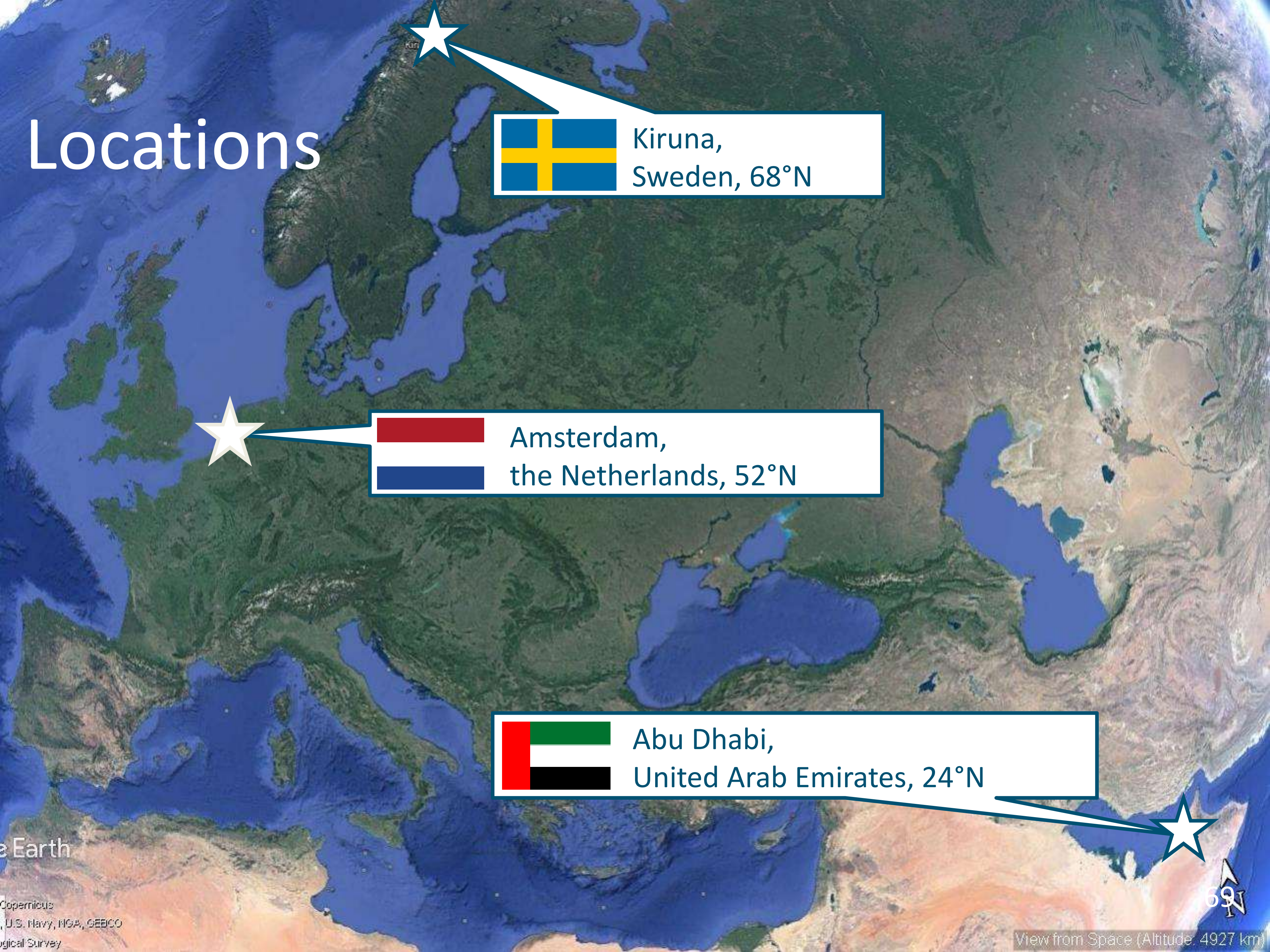
Locations


Kiruna,
Sweden, 68°N
Amsterdam,
the Netherlands, 52°N
Abu Dhabi,
United Arab Emirates, 24°N
e Earth
Copernicus
, U.S. Navy, NGA, GEBCO
ogical Survey
View from Space (Altitude: 4927 km)

The greenhouses: Netherlands

Heating, energy screen and fogging [300 g m^{-2} h^{-1}]

CO_2 setpoint 800 vpm, capacity [180 kg Ha^{-1} h^{-1}]

Sweden

To match light available in NLD:
lamps 100 µmol m^{-2} s^{-1} PAR
In total 300 MJ m^{-2} $year^{-1}$

Abu Dhabi

700 W m^{-2} cooling capacity

Plant factory


5 layers: 500 μmol m^{-2} s^{-1}, 16 h/24

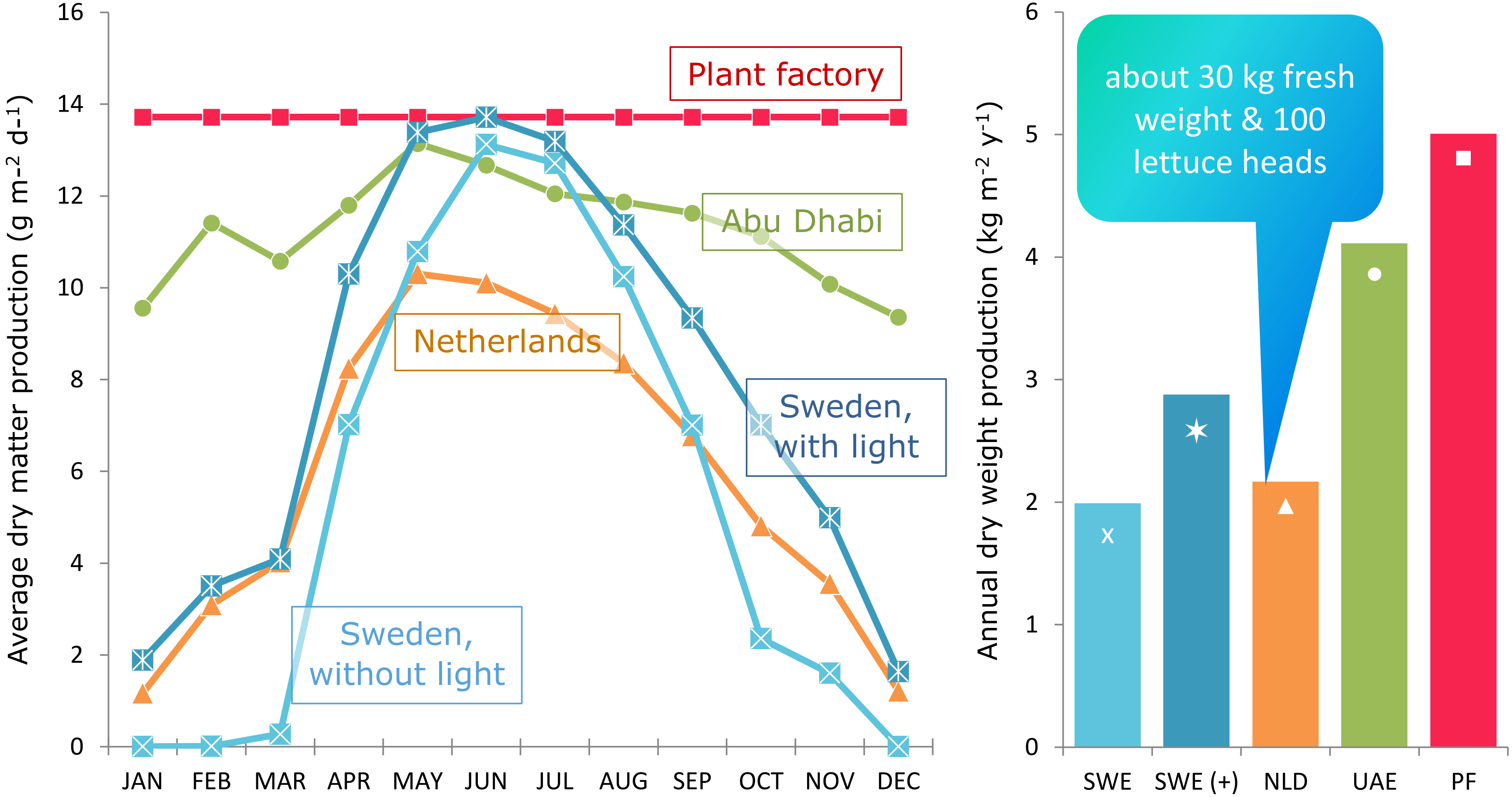
LED efficiency 2.3 μmol/J = 8.3mol/kWh

Sufficient cooling capacity

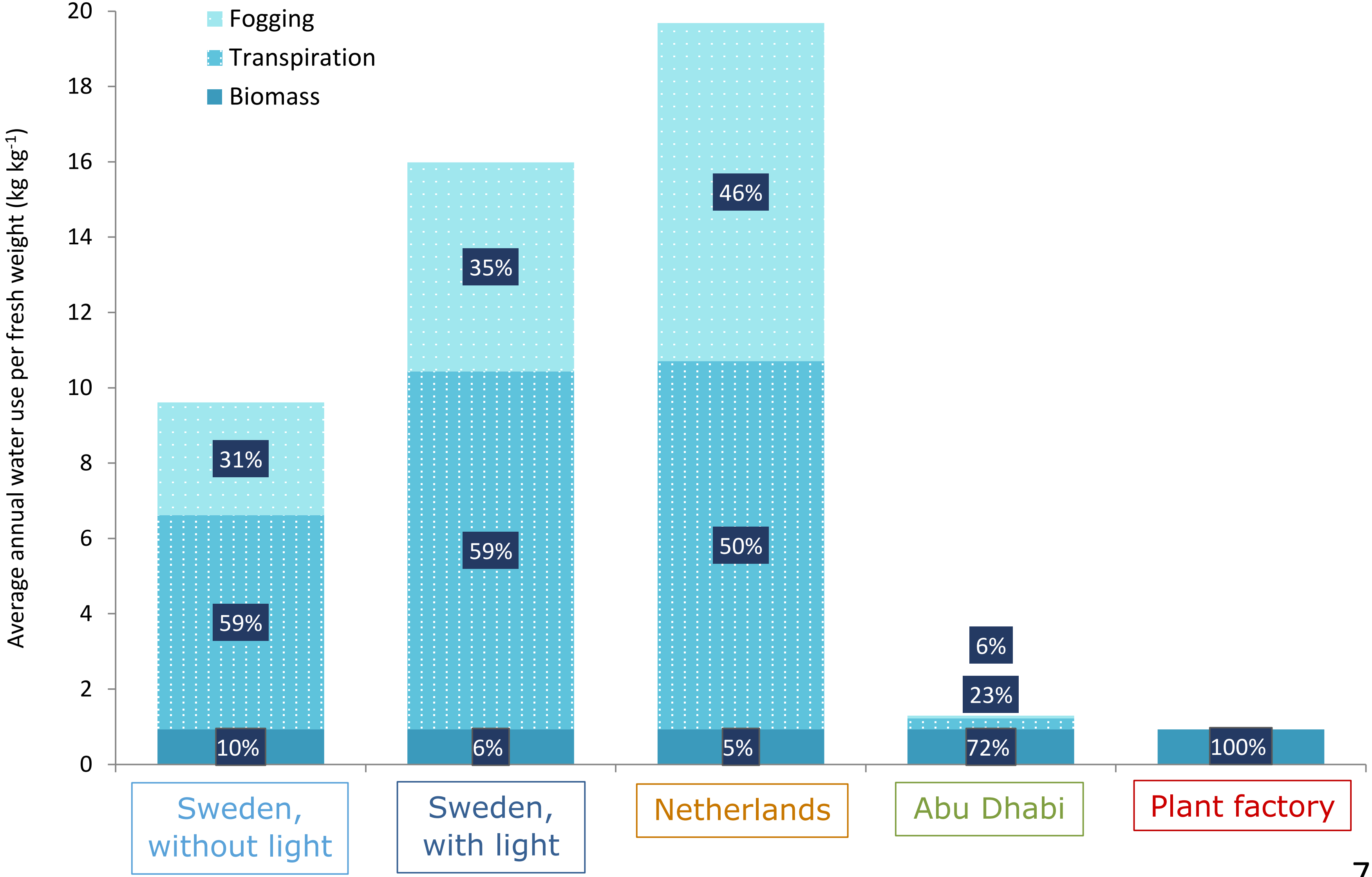
CO_2 1200 vpm, sufficient dosing capacity

Well insulated outer shell, 0.05 W m^{-2} K^{-1}

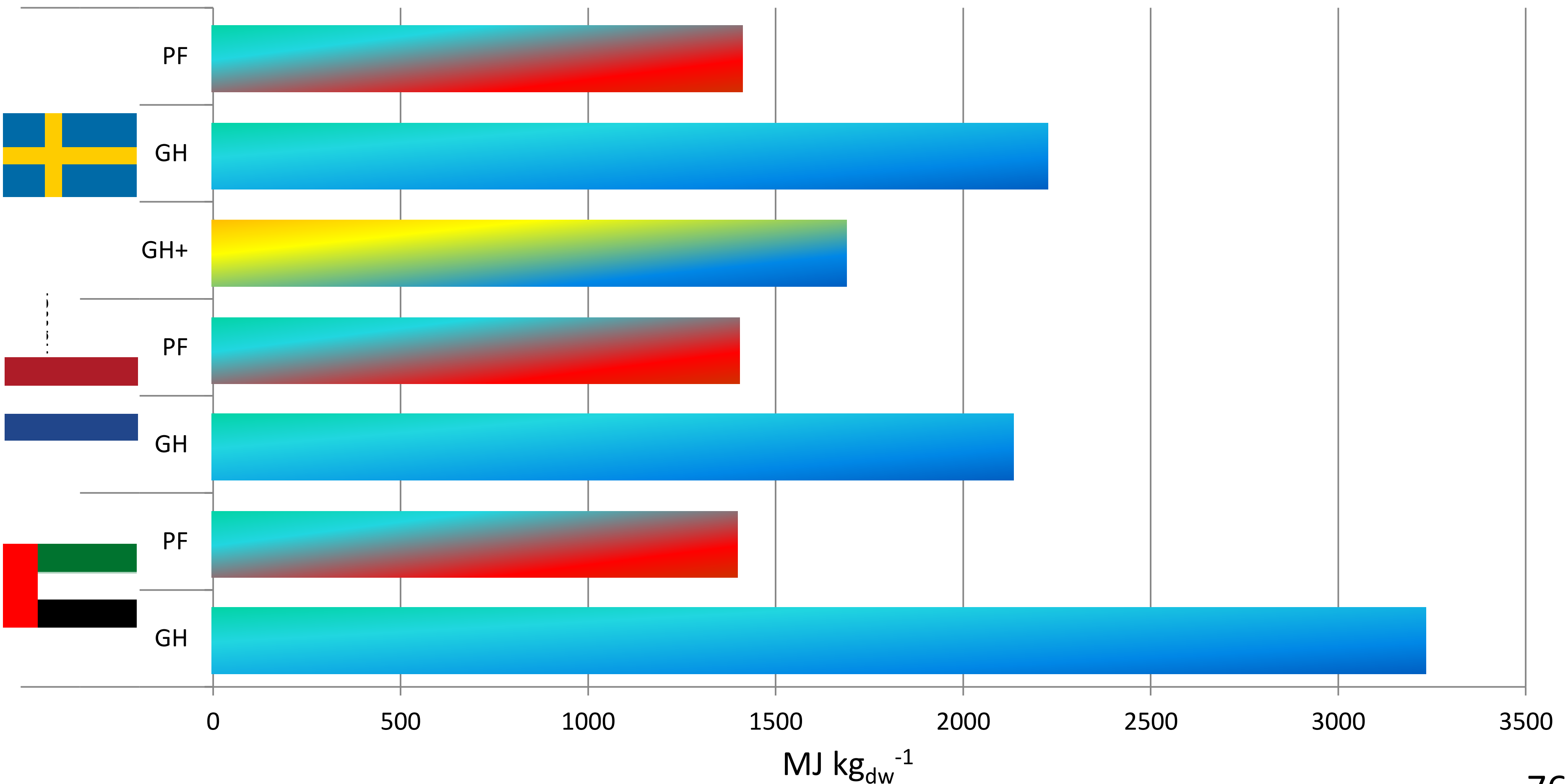

Production per unit cultivation area



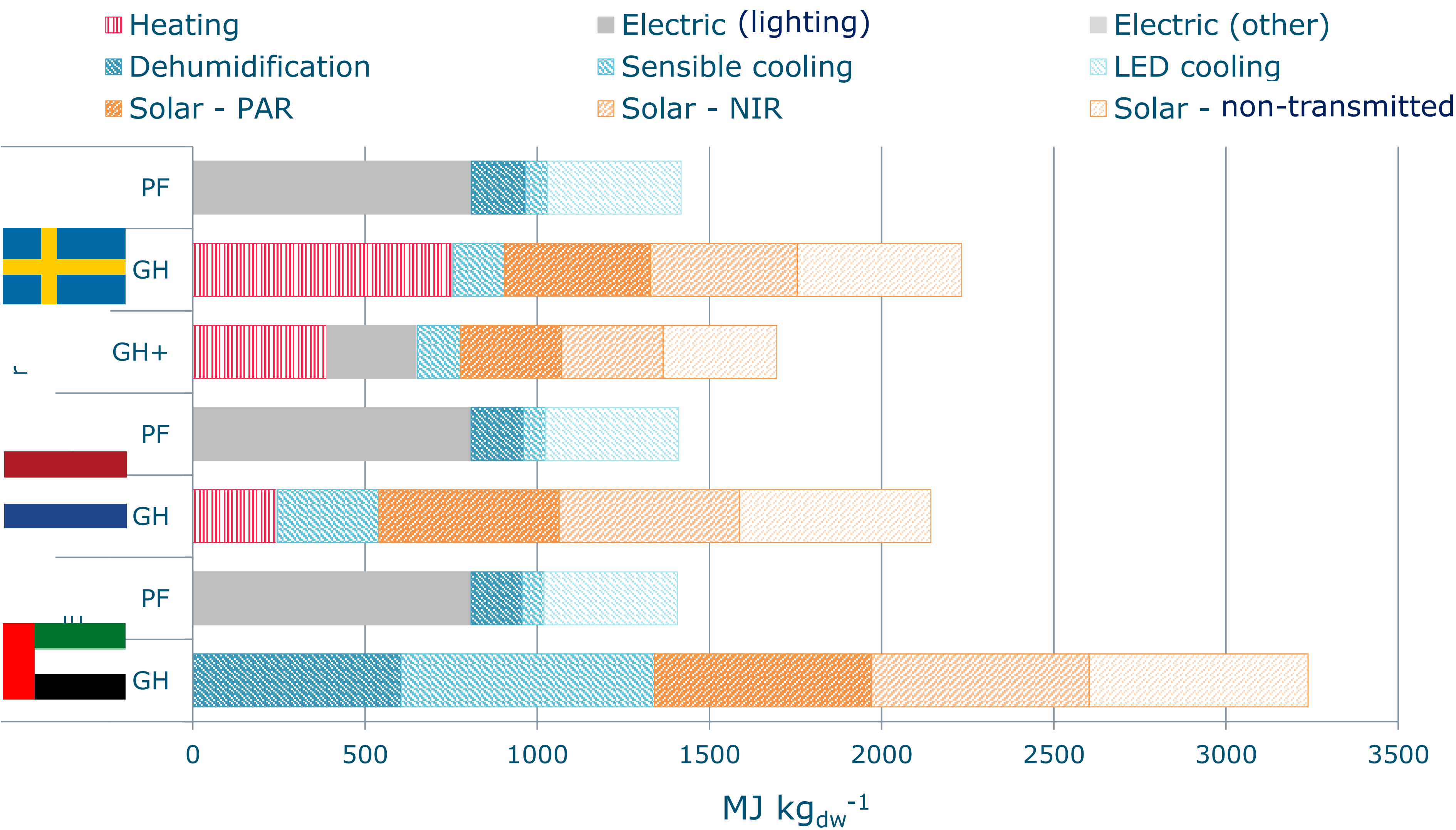
Water use per kg fresh weight



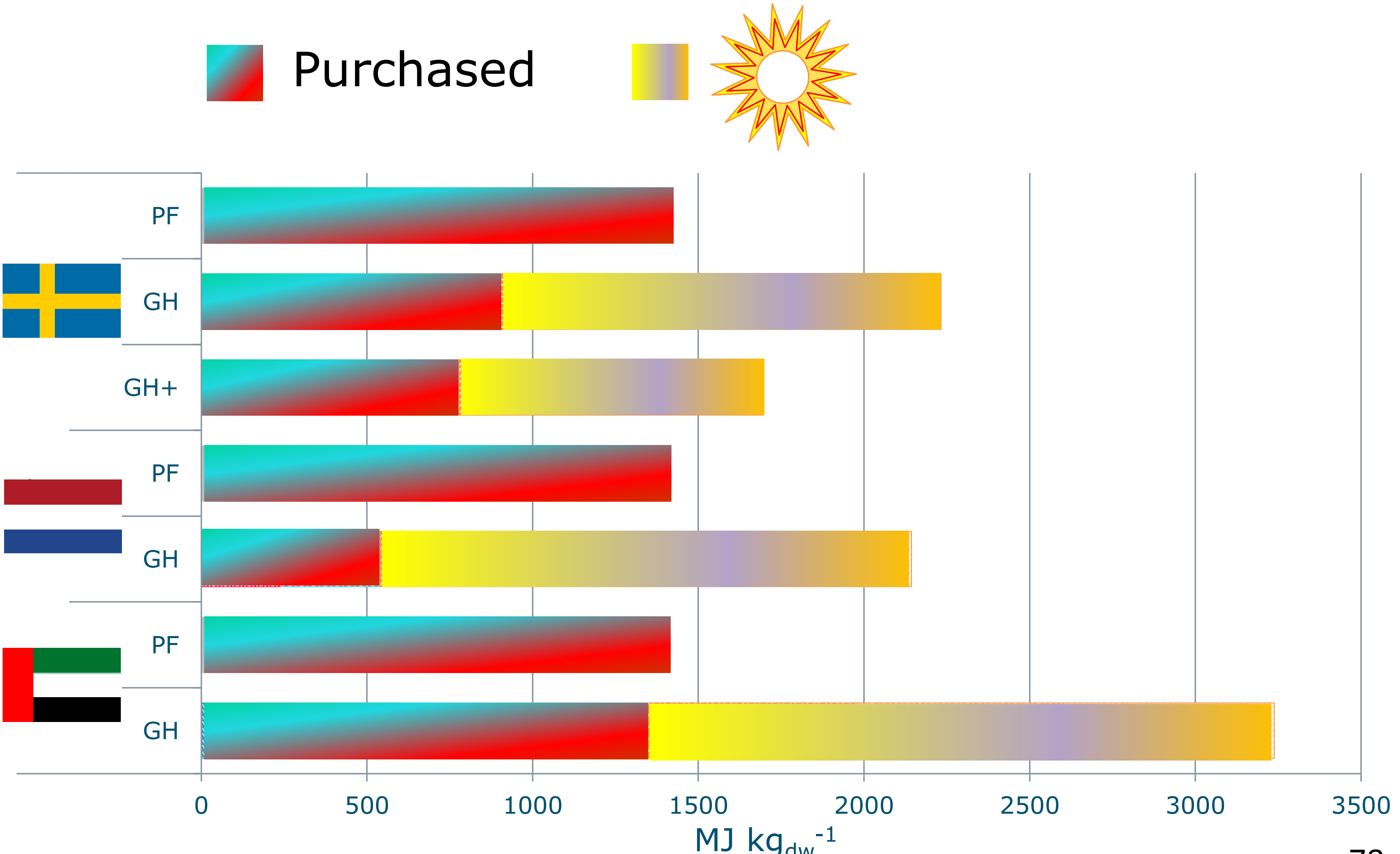
Energy use per kg dry weight



Energy use per kg dry weight



Energy use per kg dry weight



Final remarks on plant factories

- Plant factories are more efficient than greenhouses with respect to all resources (land, water, energy)

- However, in all cases the need for purchased energy is higher in plant factories than in greenhouses

- The viability of plant factories depends on the value of product and of other resources (such as land) relative to purchased energy

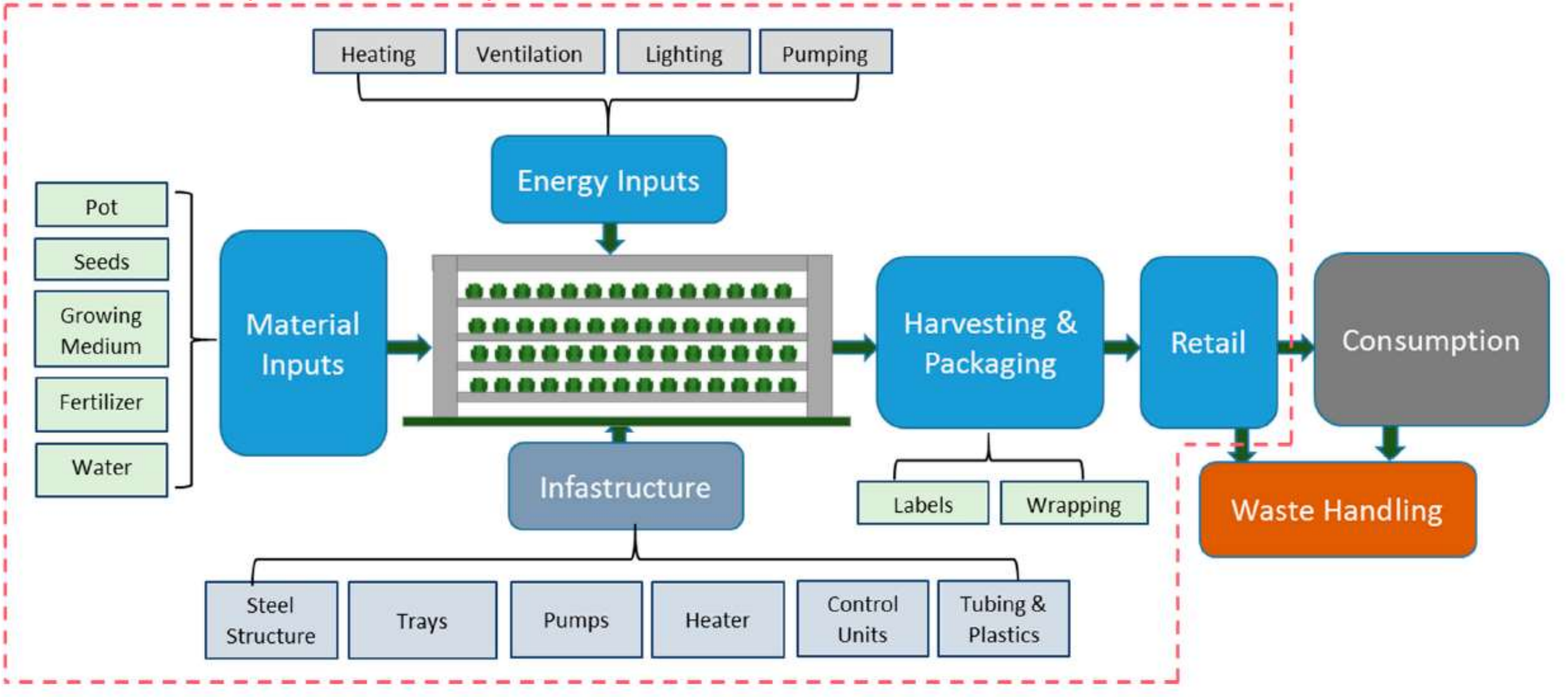
Scenarios for improving environmental performances of PFALs

Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden.

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Grönska Vertical Farm (Stockolm, Sweden)

Dashed line represents the system boundaries.



Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Grönska Vertical Farm (Stockolm, Sweden)

Plastic pot

Garden soil

Wrapped in waxed paper

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Grönska Vertical Farm (Stockolm, Sweden)

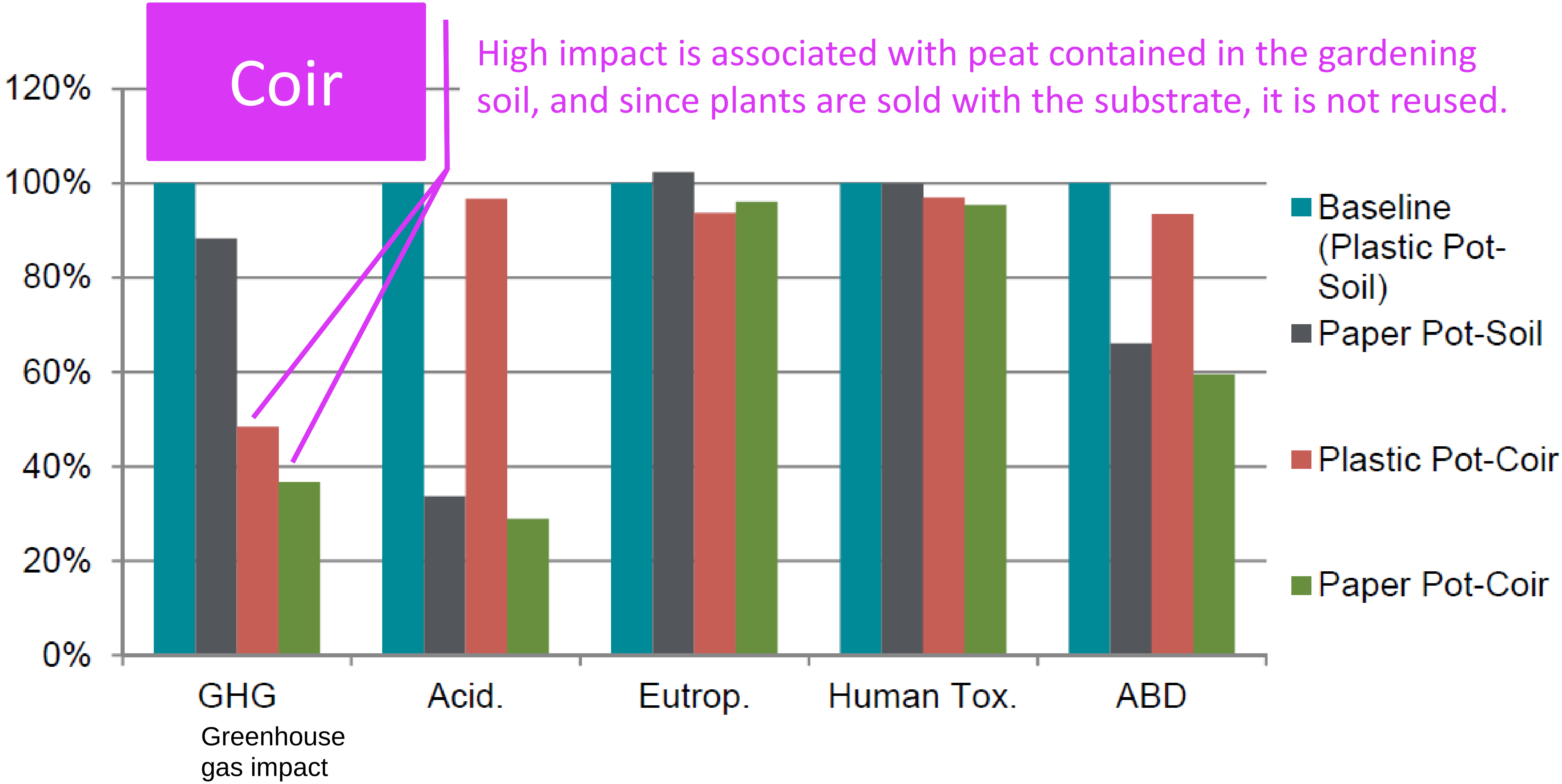
Plastic or paper pot?

Garden soil or coir?

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Grönska Vertical Farm (Stockolm, Sweden)

High impact is associated with peat contained in the gardening soil, and since plants are sold with the substrate, it is not reused.



Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

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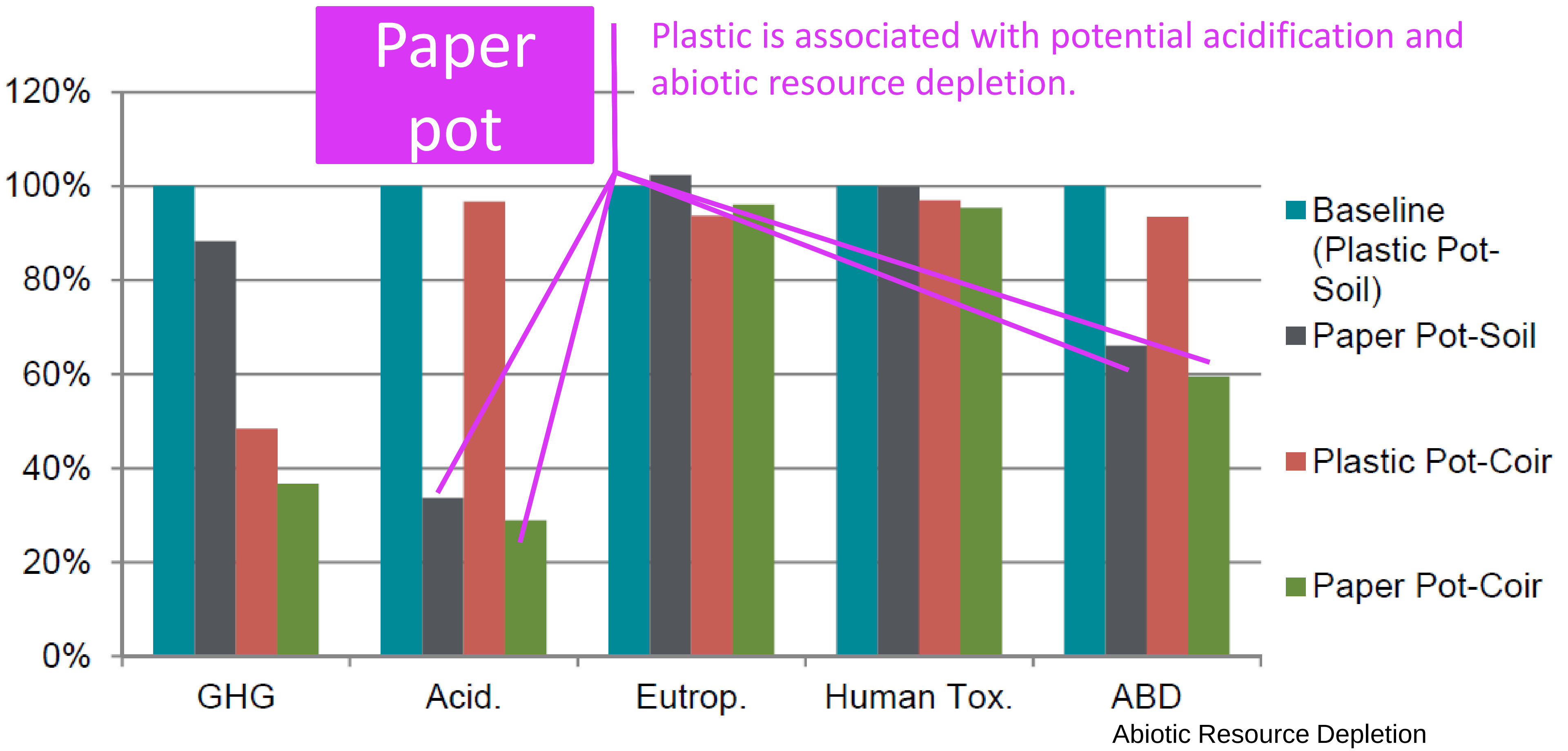
Grönska Vertical Farm (Stockolm, Sweden)



Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Grönska Vertical Farm (Stockolm, Sweden)

Swedish mix

Nuclear

Hydro

Electricity by Swedish mix or Nordic mix?

Nordic mix

Larger fossil share

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

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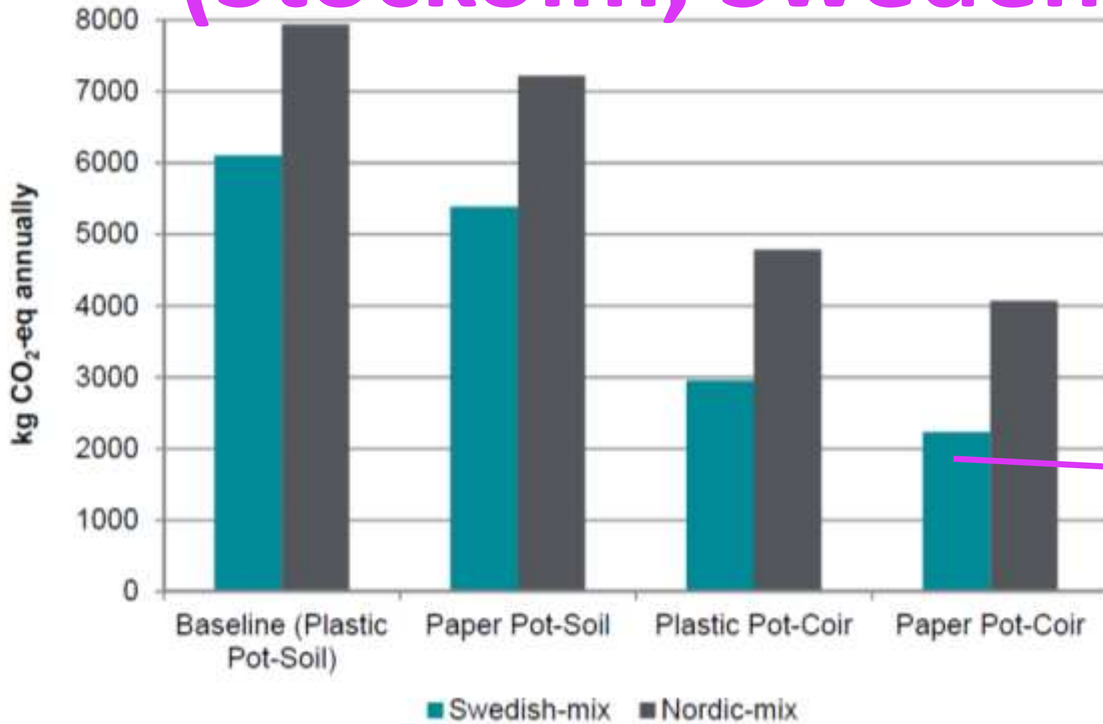
Grönska Vertical Farm (Stockolm, Sweden)

Swedish mix

Nuclear

Hydro



Swedish mix!

Nordic mix

Larger fossil share

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

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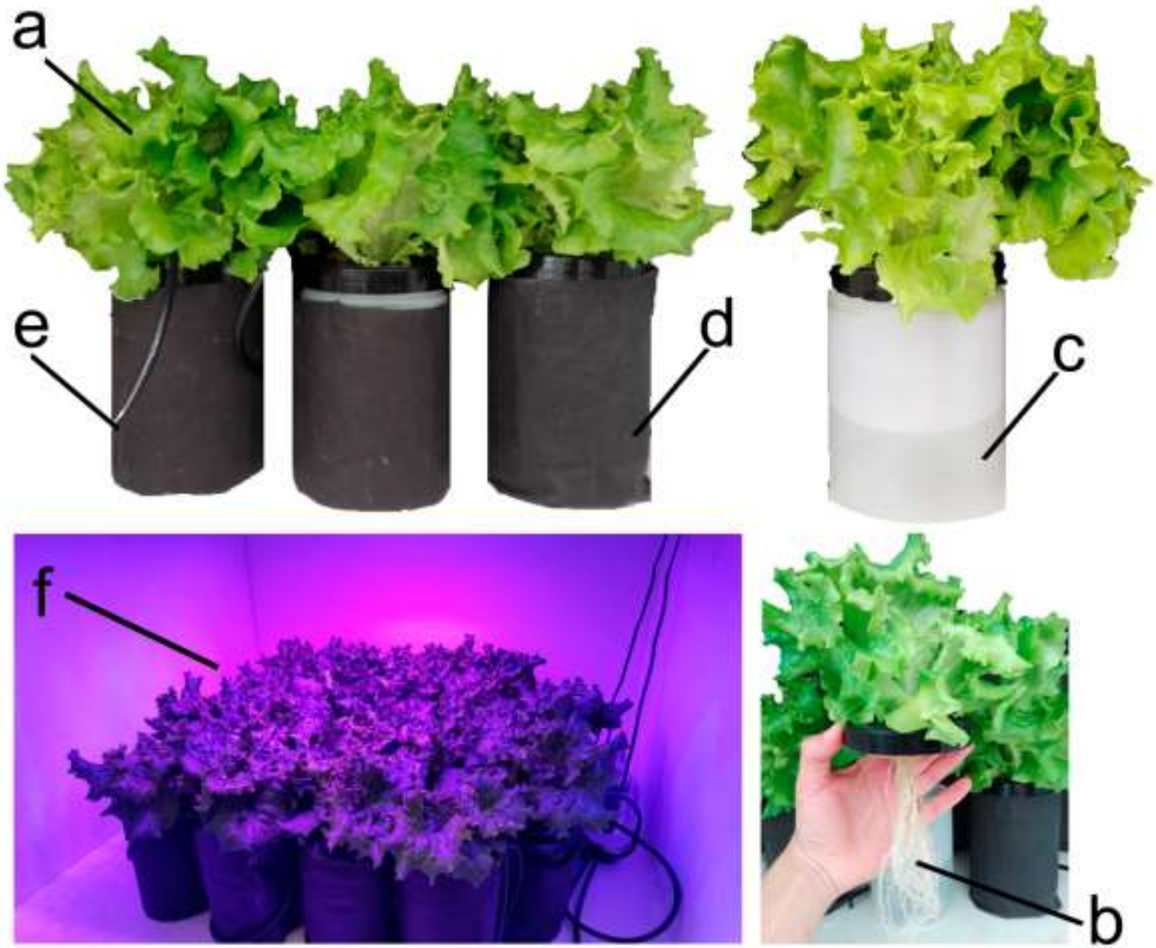
How can light management improve sustainability of indoor farming systems?

Pennisi, G., Sanyé-Mengual, E., Orsini, F., Crepaldi, A., Nicola, S., Ochoa, J., Fernandez, J.A., Gianquinto, G. 2019. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability, 11(15), 4063. doi: 10.3390/su11154063.

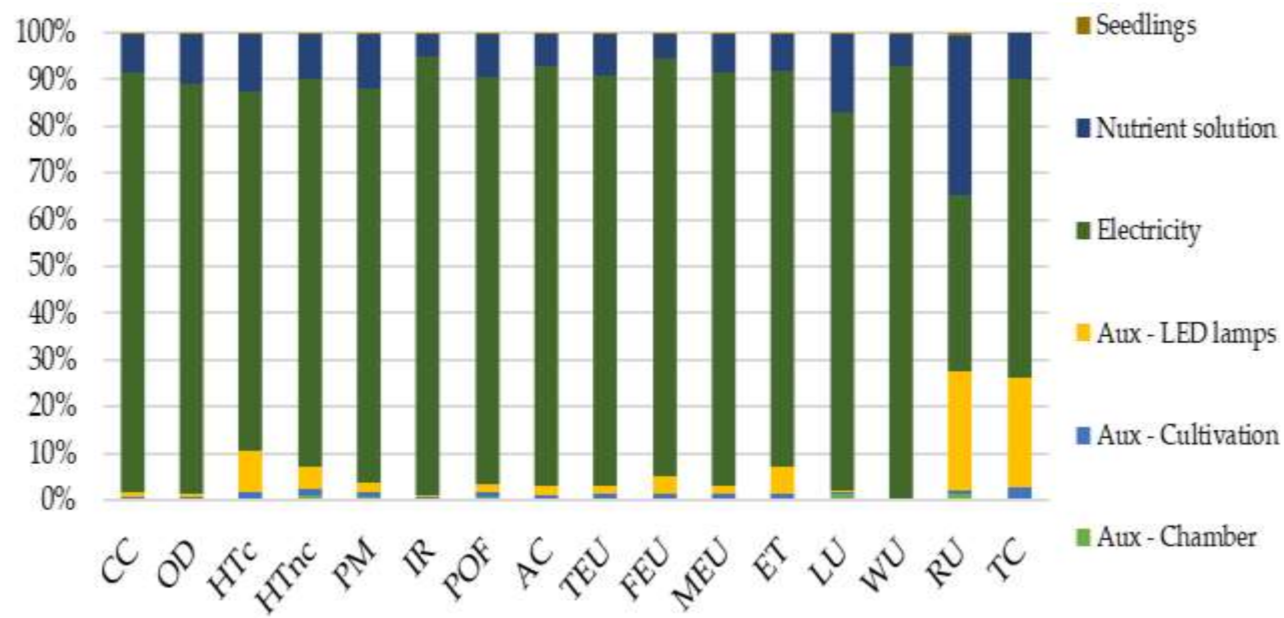
Growing systems used for the experimentation



Plants (**a**) grown on individual deep water culture hydroponic systems where the root system (**b**) floats into the nutrient solution (**c**), contained in a plastic jar and screened from light by a black cloth (**d**). Constant aeration of the nutrient solution is provided by air pumps and distributed to individual growing systems through pipes (**e**). Each light treatment is allocated to a light insulated compartment (**f**) of a climate controlled chamber, with white-painted walls and fans allowing for air recirculation.

Pennisi, G., Sanyé-Mengual, E., Orsini, F., Crepaldi, A., Nicola, S., Ochoa, J., Fernandez, J.A., Gianquinto, G. 2019. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability, 11(15), 4063. doi: 10.3390/su11154063.

Lettuce environmental assessment

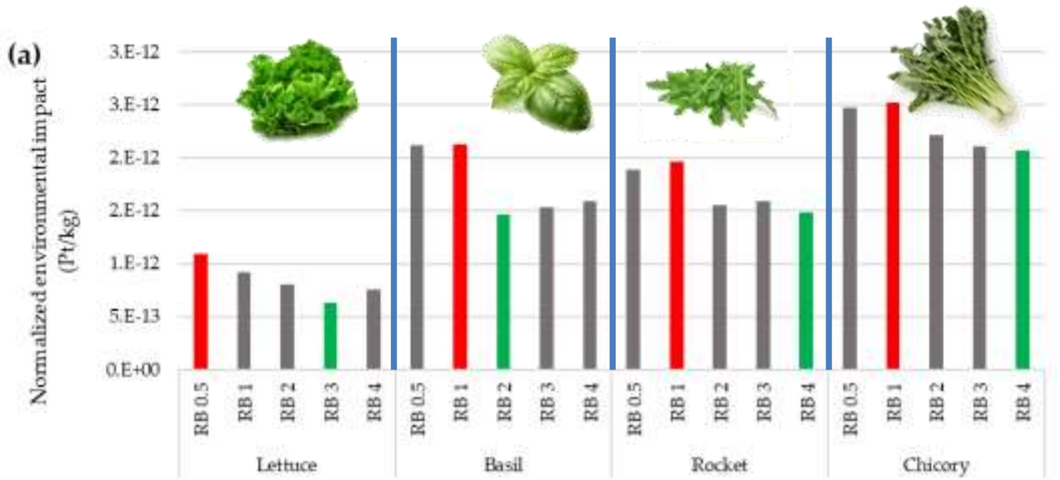


Electricity accounts for 77-93% of environmental impact and 64% of economic costs of production

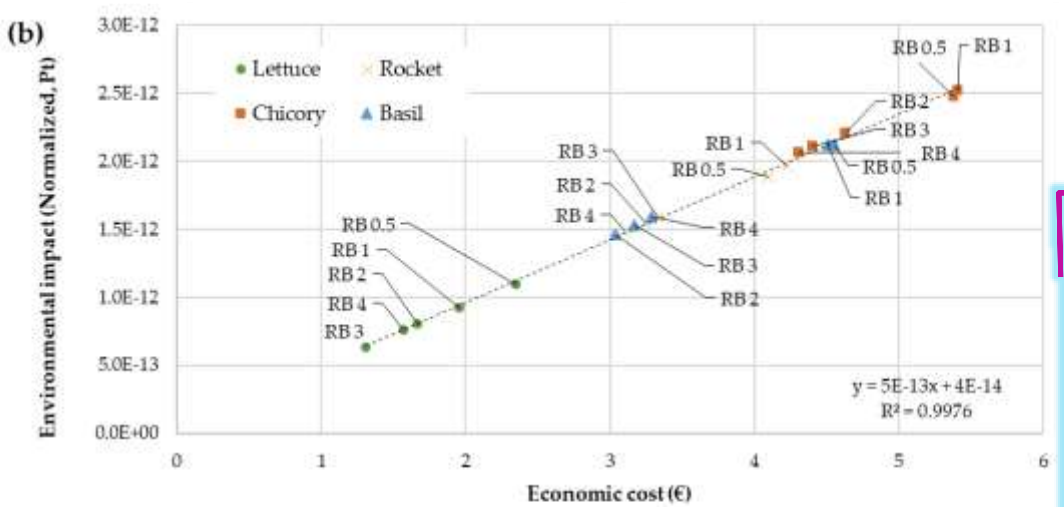
Contribution of the different elements of the life cycle inventory to the impact for lettuce production in RB0.5 treatment. Midpoint categories are climate change (CC), ozone depletion (OD), human toxicity, cancer effects (HTc), human toxicity, non-cancer effects (HTnc), particulate matter (PM), ionising radiation (IR), photochemical ozone formation (POF), acidification (AC), terrestrial eutrophication (TEU), freshwater eutrophication (FEU), marine eutrophication (MEU), ecotoxicity (ET), land use (LU), water use (WU), resources use (RU).

Pennisi, G., Sanyé-Mengual, E., Orsini, F., Crepaldi, A., Nicola, S., Ochoa, J., Fernandez, J.A., Gianquinto, G. 2019. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability, 11(15), 4063. doi: 10.3390/su11154063.

Crop environmental assessment



Normalized and weighted environmental impacts of the different crops and LED treatments. For each crop, least environmental impacting (green) and most environmental impacting (red) LED treatments are indicated.



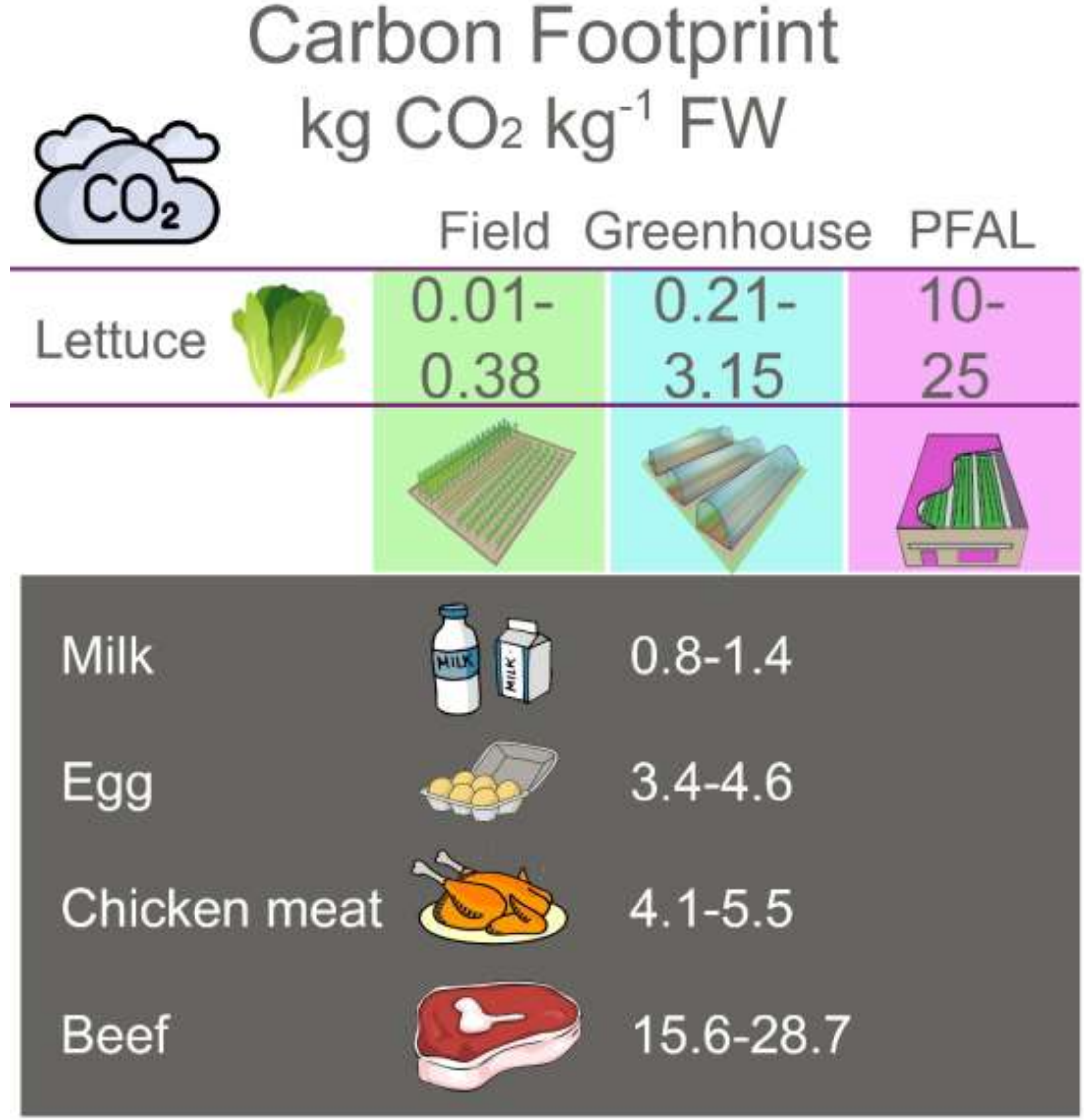
Eco-efficiency assessment of crops and LED treatments in indoor farming with reference to the production of 1 kg of fresh product.

Lettuce = least impacting crop.

Best environmental performences at RB2 (basil), RB3 (lettuce) and RB4 (rocket and chicory)

Pennisi, G., Sanyé-Mengual, E., Orsini, F., Crepaldi, A., Nicola, S., Ochoa, J., Fernandez, J.A., Gianquinto, G. 2019. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability, 11(15), 4063. doi: 10.3390/su11154063.

How much CO_2 is released per kg of food produced?



Environmental assessment of selected food products in response to the cropping system (*Source: Orsini et al., 2020, Sustainable use of resources in indoor farms with artificial lighting. European Journal of Horticultural Sciences, in press*).

Conclusive remarks

Where to go for sustainable indoor farming?

- Improving water use efficiency through appropriate light management and condensation of air humidity;
- Reducing land use, through adequate growing systems, dynamic plant spacing and crop layering;
- Reducing energy needs, by adoption of tri-generation systems and improved light use efficiency by appropriate light management (spectrum, photoperiod and intensity);

- Improving PFAL environmental performances by coupling co-generation, absorption chiller and PV electricity.
- Adequately choose energy sources, least impacting crops, improved spectral composition and adequate crop input.

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Tecnologie Agroalimentari

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western balkans urban agriculture initiative

BUGI

Co-funded by the
Erasmus+ Programme
of the European Union

western Balkans Urban aGriculture Initiative