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

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ARTICLE INFO

*Keywords:*
Artificial lighting
Energy use
Lettuce
Urban agriculture
Vertical farm
Water use

ABSTRACT

Research on closed plant production systems, such as artificially illuminated and highly insulated plant factories, has offered perspectives for urban food production but more insight is needed into their resource use efficiency. This paper assesses the potential of this 'novel' system for production in harsh climates with either low or high temperatures and solar radiation levels.

The performance of plant factories is compared with cultivation in traditional greenhouses by analysing the use of resources in the production of lettuce. We applied advanced climate models for greenhouses and buildings, coupled with a lettuce model that relates growth to microclimate. This analysis was performed for three different climate zones and latitudes (24–68°N).

In terms of energy efficiency, plant factories (1411 MJ $kg^{-1}$ dry weight) outperform even the most efficient greenhouse (Sweden with artificial illumination; 1699 MJ $kg^{-1}$ dry weight). Additionally, plant factories achieve higher productivity for all other resources (water, $CO_2$ and land area). With respect to purchased energy, however, greenhouses excel as they use freely available solar energy for photosynthesis. The production of 1 kg dry weight of lettuce requires an input of 247 kWhe in a plant factory, compared to 70, 111, 182 and 211 kWhe in greenhouses in respectively the Netherlands, United Arab Emirates and Sweden (with and without additional artificial illumination).

The local scarcity of resources determines the suitability of production systems. Our quantitative analysis provides insight into the effect of external climate on resource productivity in plant factories and greenhouses. By elucidating the impact of the absence of solar energy, this provides a starting point for determining the economic viability of plant factories.

## 1. Introduction

By midcentury, the number of people living in cities is likely to reach the level of the world's total population in 2002; the urban population is expected to increase from 3.6 billion in 2011 to 6.3 billion in 2050 (UN, 2014). The supply chains to feed the expanding cities will become increasingly complex, which will have a major impact on urban and rural areas (Newcombe and Nichols, 1979; Rosenzweig and Liverman, 1992; Kennedy et al., 2007; Lambin and Meyfroidt, 2011). It has often been suggested that urban agriculture could ensure a supply of locally produced, fresh food. Given the financial value of urban space, an economically viable venture would require exceptionally high productivity.

One proposed solution is the use of closed production systems such as plant factories and vertical farms (Seginer and Ioslovich, 1999; Kozai et al., 2006; Kozai, 2013b). A vertical farm can be considered as a multi-storey plant factory. Closed systems are designed to maximise production density, productivity and resource use efficiency (Kozai, 2013a). High productivity is achieved by adapting the interior climate to achieve uniform lighting, temperature and relative humidity through minimising the interaction with the exterior climate. Limiting this interaction can also benefit the efficient use of energy, water and $CO_2$ (Goto, 2012).

The evident shortcoming of this typology is the high energy (electricity) demand for artificial illumination, which is needed for photosynthesis. Furthermore, the combination of high-density crop production, limited volume and lack of natural ventilation is likely to induce a high demand for cooling and vapour removal (Graamans et al., 2017).

In contrast, greenhouse horticulture consists of a (semi-)controlled environment which uses primarily solar energy for photosynthesis as well as for heating. Excess energy can be discharged by ventilation and any deficits or surplus can be compensated by heating or cooling. The

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https://doi.org/10.1016/j.agsy.2017.11.003
Received 27 July 2017; Received in revised form 9 November 2017; Accepted 10 November 2017
Available online 23 November 2017
0308-521X/ 

transparent, conductive design of greenhouses is a trade-off between solar energy and the influence of the exterior climate. The relation between the costs (heating and cooling) and benefits (solar radiation) of greenhouse production largely depends on the latitude and external climate conditions of the site (Kozai, 2013b). It can be expected that at high latitudes solar radiation no longer offsets the energy being lost through the greenhouse cover. The opposite may occur at low latitudes, where the incoming solar energy cannot be discharged by natural ventilation. In these situations evaporative and/or active cooling would become necessary.

Plant factories are now being used for the commercial production of leafy greens, but their potential remains uncertain. In order to achieve economic viability, the increased resource productivity and/or the value of additional services would have to outweigh the disadvantage of the absence of solar energy.

### 1.1. Objective

The objective of this study is to quantify the resource requirement for lettuce production in greenhouses and plant factories and to analyse how this requirement is affected by external climate conditions.

### 1.2. Outline

We couple an established model for lettuce growth with accepted models for the simulation of climate and resource requirements in either plant factories or greenhouses. Subsequently, we calculate and analyse the resource requirement of lettuce production in the two growing systems, each in three climates.

## 2. Methodology

This study consists of a performance analysis of plant factories and greenhouses at three different locations. To this end, we analyse resource expenditure for lettuce production. The resource expenditure of each facility is the result of internal and external gains as well as the use of electricity, water and $CO_2$. These figures were calculated and compared. Greenhouse and building simulation software had to be used, since the two typologies require a different format. Ultimately, the production output, climatic performance and related resource consumption were analysed for each facility.

### 2.1. Model selection

#### 2.1.1. KASPRO for greenhouses

Given the differences in the construction of greenhouses and plant factories, different simulation models had to be applied. The design of greenhouses implies considerable interaction with the exterior climate. This causes substantial fluctuations in the interior climate, since control actuators have limited capacity. Therefore, a dynamic model is needed to calculate these variations. In this study we used KASPRO (De Zwart, 1996), an advanced, dynamic model to calculate the climate in greenhouses. It consists of sub-models that are based on the energy and mass balance of the greenhouse elements. The model takes full account of the interdependence of the greenhouse characteristics and the various climate control actuators, accounting for their limited capacity. More details of this model are described by De Zwart (1996), Luo et al. (2005a), Luo et al. (2005b) and Katsoulas et al. (2015).

#### 2.1.2. DesignBuilder for plant factories

Unlike greenhouses, plant factories are closed systems, consisting of a highly insulating and airtight structure (Kozai, 2013a). Detailed dynamic greenhouse models, such as KASPRO, are less suitable for calculating the limited interaction between the interior and the exterior climate as well as the high internal heat loads. Furthermore, calculating the energetic requirements of plant factories in KASPRO would require considerable modification and validation of the energy balance. Therefore, we selected EnergyPlus in combination with DesignBuilder (2016).

EnergyPlus is a building energy simulation program with three basic components – a simulation manager, a heat and mass balance simulation module and a building systems simulation module (Crawley et al., 2001). We used DesignBuilder (2016) for simulating the energy consumption of the plant factory, as this program is considered the most complete graphic user interface for EnergyPlus.

DesignBuilder is not a dynamic simulation model. This is not a limitation, as plant factories have just two states (photo-/dark period), each with a constant climate throughout. It is essential to calculate the energetic behaviour of the crop in both states – how it transpires, reflects light and exchanges heat and radiation. Cooling and vapour removal are quite different processes and the relation between sensible and latent heat is a key factor in the energy demand. Therefore, the energy balance must be based on an accurate estimate of the crop transpiration coefficient, i.e. the fraction of the radiation load that is dissipated by the crop as latent heat. We have integrated the energetic behaviour into the simulations, following the method described by Graamans et al. (2017). We have taken into account an average LAI of 2.1, according to Tei et al. (1996), in order to represent a facility where all stages of development are simultaneously present, as is common in actual practice.

The energetic behaviour of lettuce was calculated for the conditions of photo- and dark periods (Table 1). The various positive energetic fluxes were set as equipment gains in DesignBuilder; the negative sensible heat transfers were set as process gains. The cooling load for maintaining a constant temperature of the nutrient solution (Section 2.3.4) was calculated manually and integrated into the total sensible cooling load. We used Fourier's law of heat conduction to calculate the heat transfer across container and cover. For this calculation we assumed a constant temperature of the nutrient solution of 24 °C, air temperatures of 30/24 °C during photo − /dark periods, a conductive surface area of 2.2 $m^2$ per $m^2$ cultivation area, a thickness of 50 mm and a U-value of 0.03 $W\,m^{-2}\,k^{-1}$. The conductive surface area is based on suspended, extruded containers with a rectangular cross section of 850 × 130 mm and a nutrient solution depth of 125 mm.

### 2.2. Lettuce production in relation to climate

Differences between the interior climates of greenhouses and plant factories result in differences in plant production. The production in both types of facility determines their respective energetic performances. To this end, the model described by Van Henten (1994) was implemented in computational software (MATLAB, 2016). This is a dynamic growth model that simulates various physiological processes in butterhead lettuce (*Lactuca sativa* var. *capitata* L.). The model determines crop growth rate by distinguishing between growth of structural (e.g. glucose, sucrose, starch) and non-structural (e.g. cell walls, cytoplasm) dry weight. Non-structural dry weight is calculated as a function of gross canopy photosynthesis, respiration and transformation into structural material. Structural dry weight is a function of non-structural dry weight and canopy temperature. We took total dry matter (shoot and root) as the most adequate indicator of production in different conditions. This method negates the effects of commercial and crop management strategies, as well as possible variations in dry matter partitioning between root and shoot. In practice the roots contain approximately 8% of the total dry matter (He and Lee, 1998a, 1998b; Frantz et al., 2004). Furthermore, we assumed a fixed dry matter content of 7% (Koudela and Petříková, 2008; Gent, 2014), an average LAI of 2.1 (Section 2.1.2) and an initial dry weight of 0.48 $g\,m^{-2}$ cultivation area.

The Van Henten (1994) model reduces the three-dimensional crop canopy to a single plane (cultivation area), though it does not address the plant density. This limitation inhibits modelling the transplanting and the respacing of crops. Respacing is done in plant factories and

**Table 1**
Key model parameters for the design of plant factories and greenhouses in Sweden (SWE), the Netherlands (NLD) and the United Arab Emirates (UAE).

| Parameter | Plant factories | Greenhouse: SWE | Greenhouse: NLD | Greenhouse: UAE |
|---|---|---|---|---|
| Location | *See Greenhouse* | 67.83° N, 20.34° E | 51.99° N, 5.66° E | 24.45° N, 54.65° E |
| ASHRAE/Köppen-Geiger climate classification | *See Greenhouse* | 7/Dfc | 4A/Cfb | 1B/BWh |
| Typology | Closed system | Venlo type | Venlo type | Venlo type |
| Dimensions (m) | 100 × 100 × 6 | 100 × 100 × 6 | 100 × 100 × 6 | 100 × 100 × 6 |
| Production area ($m^2$) | 50,000 | 10,000 | 10,000 | 10,000 |
| Average transmissivity[a] (%) | 0 | 61.5/60.0[b] | 63.8 | 60.0 |
| Façade construction | Gypsum – PUR – Gypsum | Standard single glass cover[d] | Standard single glass cover[d] | Standard single glass cover[d] |
| Heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) | 0.05[c] | 5.70 | 5.70 | 5.70 |
| Heating setpoints photo-/dark period (°C) | 24/24 | 12/9 | 12/9 | N/A |
| Cooling/ventilation setpoints photo-/dark period (°C) | 30/30 | 16/13 | 16/13 | 24/17 |
| P-Band ventilation | N/A | (5; 5); (15; 4)[e] | (5; 5); (15; 4)[e] | N/A |
| Relative humidity setpoints photo-/dark period (%) | $RH_{min}$ = 65/65<br>$RH_{max}$ = 90/90 | $RH_{max}$ = 85/90<br>$RH_{min}$ = 80 | $RH_{max}$ = 85/90<br>$RH_{min}$ = 80 | $RH_{max}$ = 85/90<br>$RH_{min}$ = 70 |
| P-Band relative humidity | N/A | (5; 10); (20; 5)[f] | (5; 10); (20; 5)[f] | N/A |
| Heating system | HVAC (forced circulation) | Boiler (gas)<br>Low metallic pipes | Boiler (gas)<br>Low metallic pipes | N/A |
| Heating capacity ($W\ m^{-2}$) | N/A | 150 | 100 | N/A |
| Cooling system | HVAC (forced circulation)<br>Fancoil unit<br>Air cooled chiller | Natural ventilation<br>Fogging system ($H_2O$) | Natural ventilation<br>Fogging system ($H_2O$) | Natural ventilation<br>Fogging system ($H_2O$)<br>Heat exchanger<br>Air cooled chiller |
| Active cooling capacity ($W\ m^{-2}$) | N/A | 0 | 0 | 700 |
| Fog system setpoints[g] | N/A | $T_{min}$ = 20 °C (summer[h])<br>$T_{min}$ = 22 °C (winter[h])<br>$RH_{min}$ = 80% | $T_{min}$ = 20 °C (summer[h])<br>$T_{min}$ = 22 °C (winter[h])<br>$RH_{min}$ = 80% | $T_{min}$ = 25 °C<br>$RH_{min}$ = 70% |
| Fog system capacity ($g\ m^{-2}\ h^{-1}$) | N/A | 300 | 300 | 300 |
| Energy saving screen setpoints[i] | N/A | (− 20; 300); (3; 200); (4; 10)<br>$T_{out}$ (max): 10 °C | (− 20; 300); (3; 200); (4; 10)<br>$T_{out}$ (max): 10 °C | N/A |
| $CO_2$ levels (μmol $mol^{-1}$) | 1200 | 800 | 800 | 800 |
| $CO_2$ dosing capacity ($kg\ ha^{-1}\ h^{-1}$) | | 180 | 180 | 150 |
| Lighting system | LED | N/A/HPS[j] | N/A | N/A |
| Radiation (μmol $m^{-2}\ s^{-1}$) | 500 | Natural/Natural + 100[j] | Natural | Natural |
| Duration photo-/dark period | 16 h/8 h | Natural/Natural + artificial illumination[j] | Natural | Natural |
| Growth cycle (d) | 30[k] | 60[l] | 60[l] | 60[l] |

[a] Average transmissivity is defined as the average of greenhouse daytime transmission values for the entire year (Appendix B).
[b] Average transmissivity without (GH) and with (GH +) shadows created by the lighting installation, respectively.
[c] Standards for insulation and airtightness were exceeded to simulate a closed system (Kozai et al., 2006; Kozai, 2013a).
[d] Optical properties are listed in Appendix A.
[e] Vents are fully opened when interior temperature exceeds the setpoint by ≥ 5 °C at $T_{out}$ < 5 °C. Vents are also fully opened if interior temperature exceeds the setpoint by ≥ 4 °C at $T_{out}$ ≥ 15 °C. In between, linear interpolation is used.
[f] Vents are fully opened when interior relative humidity exceeds the setpoint by ≥ 10% at $T_{out}$ ≤ 5 °C. Vents are also fully opened when interior relative humidity exceeds the setpoint by ≥ 5% at $T_{out}$ ≥ 20 °C. In between, linear interpolation is used.
[g] Fogging is activated when the interior climate exceeds the temperature setpoint or falls below the relative humidity setpoint.
[h] Summer runs from 01 APR - 30 SEP and winter from 01 OCT - 31 MAR.
[i] Screens are closed at − 20 °C < $T_{out}$ < 3 °C if radiation is < 300 W $m^{-2}$, at 3 °C < $T_{out}$ < 4 °C if radiation is < 200 W $m^{-2}$ and at 4 °C < $T_{out}$ < 10 °C. Screens are not used at $T_{out}$ ≥ 10 °C. In between, linear interpolation is used.
[j] Values without (GH) and with (GH +) artificial illumination, respectively. The intensity and duration of the artificial lighting (average power of 55 W $m^{-2}$) were calculated to supplement natural lighting in SWE (by 299.5 MJ $m^{-2}$ of PAR, annually) to match the total PAR available in the NLD greenhouse.
[k] This cycle duration already produced crops of marketable size in plant factories.
[l] Actual practice by Dutch greenhouse lettuce growers (Vermeulen, 2016).

greenhouses to optimise light interception and minimise the required cultivation area.

The climate variables affecting crop growth are temperature, photosynthetic photon flux density (PPFD) and $CO_2$ concentration. The effect of different combinations of temperature, PPFD and $CO_2$ concentration is illustrated in Fig. 1. For this calculation we used cycles of 60 days with uniform conditions and a photoperiod of 16 h $d^{-1}$. Maximum photosynthesis is achieved at temperatures of 20–25 °C. Respiration increases with temperature and reaches a maximum at 30–35 °C. This results in a maximum dry matter production at approximately 16–17 °C.

### *2.3. Model inputs*

#### *2.3.1. Location and typology*

Three sites were selected to represent diverse latitudes and climates, namely Kiruna in Sweden (SWE: 67.8° N, 20.2° E), Amsterdam in the Netherlands (NLD: 52.0° N, 5.7° E) and Abu Dhabi in the United Arab Emirates (UAE: 24.5° N, 54.7° E). The hourly weather information for the simulations was retrieved from the EnergyPlus database (EnergyPlus, 2016a, 2016b, 2016c). This database was chosen for its comprehensiveness. Fig. 2 shows a monthly summary of solar radiation and temperature.

### 2.3.2. Geometry

A simulation was done of greenhouses and plant factories with a footprint of 100 × 100 m, a size deemed sufficient to negate border effects. The model for the plant factory assumes five production layers and that for the greenhouse just one. The greenhouse is modelled as a Venlo type, consisting of 25 spans of 4 m, with a North-South gutter, a gutter height of 6 m and a roof slope of 23°. The plant factory is modelled as a highly insulated opaque box that is illuminated by LEDs and has an overall height of 6 m. Key parameters of the model are given in Table 1.

In plant factories it is assumed that no air is exchanged with the exterior climate. Conversely, in greenhouses some air infiltration occurs, even with closed rooftop ventilators. The infiltration ($m^3\ m_{GH}^{-2}\ s^{-1}$) is assumed to linearly increase with wind velocity ($m\ s^{-1}$) with a coefficient of 8E-5.

### 2.3.3. Climatisation systems

All plant factories feature the same growing, lighting and climatisation system. The lighting system uses LEDs and its efficiency (the conversion of electric power into the irradiance of photosynthetically active radiation) was set at 52% (Royal Philips, 2015). The remaining power of 48% dissipates as sensible heat, which is extracted by water cooling to ensure optimal efficiency. It is assumed that the climatisation system has the capacity to ensure the required air temperature, humidity and $CO_2$ concentration.

Greenhouse climatisation systems, however, have fewer actuators and a limited capacity. The capacities and setpoints for the supply of heating, cooling and $CO_2$ are listed in Table 1. The use of identical hardware in greenhouses would not result in a viable growing system at each of the three locations. Therefore, the greenhouses in NLD and SWE were fitted with an energy-saving screen (non-porous, semi-transparent: 88% perpendicular light transmission), in accordance with current practice. Conversely, the greenhouse in UAE did not feature heating and screens. Artificial illumination has to be applied in the greenhouses in SWE to enable year-round production (Fig. 3). This is achieved by supplementing the low levels of solar radiation (Fig. 2). Our lighting system includes high-pressure sodium lamps with an average power of 55 W $m^{-2}$.

Similarly, there are differences in the greenhouse cooling systems. A high-pressure fogging system and natural ventilation are adequate to cool greenhouses in NLD and SWE. In the greenhouse in UAE the use of an active cooling installation is imperative, as evaporative cooling would require large amounts of water, which is scarce (Sabeh et al., 2011). Additionally, the high relative humidity of the ambient air in UAE would make evaporative cooling ineffective. Fogging systems, however, are included to increase the ratio of latent to sensible heat. This, in turn, increases the efficiency of the total heat extraction.

### 2.3.4. Climate setpoints

Climate setpoints for each growing system had to be selected carefully, as the productivity of lettuce is mainly determined by the relationship between canopy temperature, PPFD, photoperiod and $CO_2$ concentration.

For the greenhouse models, we selected climate setpoints roughly in agreement with standard local practice (Table 1). Root zone temperature was considered to be equal to air temperature, as nutrient solution tanks are commonly placed within the greenhouse without temperature control. It was also assumed that the irrigation system is completely closed (drain water is recovered and re-used) and that water and nutrient supplies are non-limiting. With respect to lighting, we made two separate calculations for SWE to capture the greenhouse with and without artificial lighting. In these calculations we simulated supplemental lighting in order to match the amount of solar photosynthetically active radiation found in NLD. This facilitates comparison, even though in practice lighting systems would probably be used for longer periods.

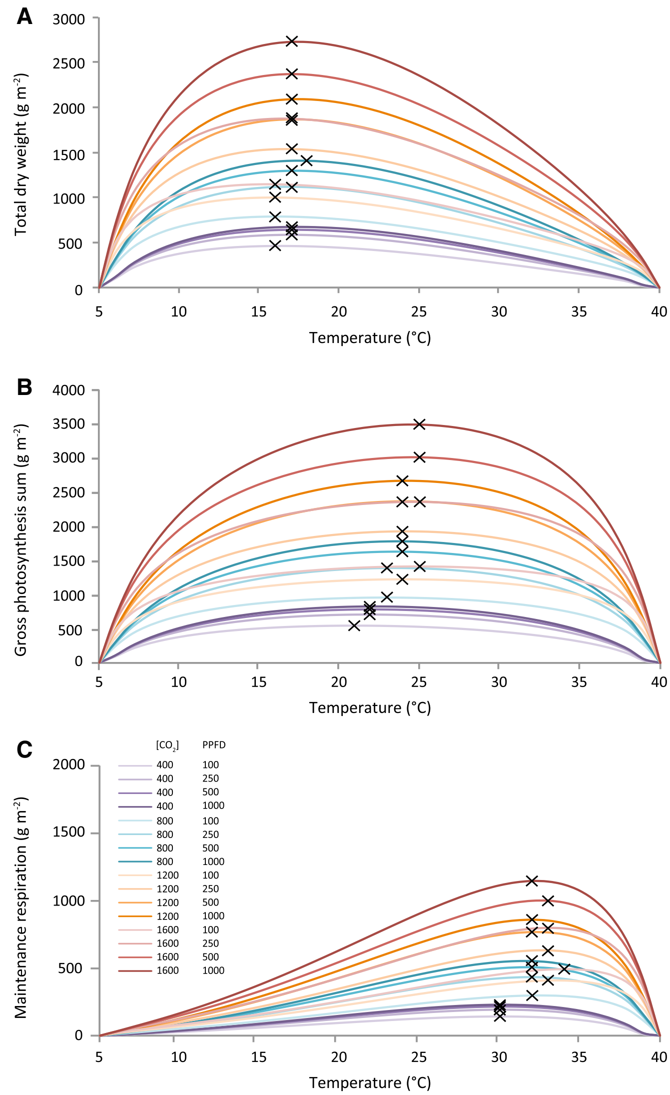


**Fig. 1.** The calculated total dry weight production (A), photosynthesis (B) and respiration (C) of lettuce at different leaf temperatures and combinations of $CO_2$ concentration (ppm) and PPFD (μmol $m^{-2}\ s^{-1}$). Calculations include a complete production cycle of 60 days, a photoperiod of 16 h $d^{-1}$, and a constant temperature during photo-/dark periods. The maximum value on each curve is indicated by X.

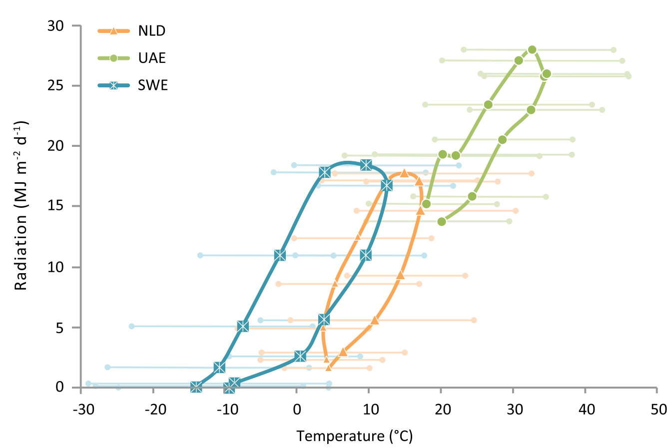


**Fig. 2.** Average daily radiation per month (MJ $m^{-2}\ d^{-1}$) and monthly average, minimum and maximum temperatures (°C) for Kiruna (SWE, stars), Amsterdam (NLD, triangles) and Abu Dhabi (UAE, circles). January is the lower left data point in each cycle.

The (low) setpoint for greenhouse air temperature would lead to an unrealistically high cooling requirement in plant factories. Therefore, the air temperature was limited to 30 °C (Hall, 1979; Farquhar et al., 1980) and the relative humidity was set at 65–90%. The root zone temperature in plant factories was limited to 24 °C to ensure the formation of compact lettuce heads (He and Lee, 1998a, 1998b; Thompson et al., 1998; Frantz et al., 2004). With respect to lighting, we assumed a PPFD of 500 µmol $m^{-2}$ (Hall, 1979) and a photoperiod of 16 h in order to prevent premature bolting (Waycott, 1995).

As there is no loss of $CO_2$ to the exterior climate in a plant factory, a smaller supply of $CO_2$ is sufficient to maintain a higher-than-ambient concentration. Therefore, the $CO_2$ concentration setpoint in plant factories exceeds the one in greenhouses (1200 versus 800 ppm).

Production in greenhouses commonly requires different cultivars and crop management than production in plant factories. The selection of slow-bolt cultivars can contribute to an efficient production at higher temperatures and longer photoperiods (Silva et al., 1999; Simonne et al., 2002; Zhao and Carey, 2009). This study does not address the selection of cultivars but instead discusses total dry matter production, on which the cultivars have a limited effect.

### 2.4. Processing model output

The simulations focus on energy loads and on the use of electricity, water and $CO_2$. Dry matter production is calculated in relation to the production climate, as stated in Section 2.2. In order to represent a facility where all stages of development occur simultaneously, we calculated the moving average in all aspects of this study. Hereafter, in addition to the three-letter codes for the country, the acronym PF refers to plant factories, and GH and GH + stand for greenhouses without and with artificial lighting, respectively.

#### 2.4.1. Energetic loads

The system loads include artificial illumination by LED, LED cooling (Section 2.3.3), sensible cooling, dehumidification, heating and installed power. The output from DesignBuilder presents the energetic loads for individual systems. The KASPRO output contains the resources required by the climatisation systems. Subsequently, these values had to be converted to system loads, following the factors listed in Table 2. The heating load ($Q_H$) in greenhouses, for instance, is determined by the gas use for heating ($G_H$) and its energy conversion efficiency ($c_G$) according to the formula:

$$Q_H = c_G \cdot G_H \tag{1}$$

Each greenhouse features a fogging system for cooling (Section 2.3.3). The evaporation of water extracts energy as sensible heat and converts it to latent heat. These systems can therefore only be considered as sensible cooling when vents are opened to extract water vapour. Subsequently, the sensible cooling load can be determined by multiplying the amount of water evaporated from the fogging system when vents are opened ($W_{C;Fog}$) by the heat capacity of water ($c_W$) according to the formula:

$$Q_{C;Sen} = c_W \cdot W_{C;Fog} \tag{2}$$

The UAE-GH has a sensible and latent cooling load. The latent (dehumidification) load ($Q_{C;Lat}$) of this greenhouse is determined by multiplying the amount of vapour condensed by the heat exchanger ($W_{Con,Hex}$) by the heat capacity of water according to the formula:

$$Q_{C;Lat} = c_W \cdot W_{Con;Hex} \tag{3}$$

Subsequently, the sensible cooling load ($Q_{C;Sen}$) can be determined by subtracting $Q_{C;Lat}$ from the total load of the heat exchanger ($Q_{C;Hex}$). Then the energy load from the fogging system and from cooling the nutrient solution ($Q_{C;Ns}$) can be integrated in the following formula:

$$Q_{C;Sen} = c_W \cdot W_{C;Fog} + Q_{C;Ns} + Q_{C;Hex} - Q_{C;Lat} \tag{4}$$

**Table 2**
The energy potential of resources as used to determine system loads from KASPRO output.

| | Zone heating | Latent cooling | Sensible cooling | Electric | Solar |
|---|---|---|---|---|---|
| Output KASPRO | Gas use ($m^3\ s^{-1}$) | Condensed water ($kg\ s^{-1}$) | Evaporated water ($kg\ s^{-1}$) | Electricity (kWhe) | Total PAR (µmol $s^{-1}$) |
| Factor | 3.17E7 ($J\ m^{-3}$) | 2.44E6 ($J\ kg^{-1}$) | 1.67E-2 ($J\ kg^{-1}$) | 1.00 | 4.57 (J $µmol^{-1}$) |

#### 2.4.2. Electricity

When calculating electricity use, we distinguish two categories: systems using only electricity and systems using other natural resources. The system loads ($Q$) for plant factories are converted to electricity use ($E$) following their respective coefficient of performance ($COP$) according to the formula:

$$E = \frac{Q}{COP} \tag{5}$$

The plant factories and the UAE-GH use electric heating and cooling (Section 2.3.3). In these models, the energetic loads can be converted to electricity use by using their COP, as listed in Table 3. These COPs were determined by taking the difference between supplied and exterior temperature, weighted for corresponding load (Meggers et al., 2012).

The SWE-GH, SWE-GH + and NLD-GH use heating by means of natural gas and cooling by means of water (fogging). Therefore, their energetic loads should not be converted using COPs. Instead, we consider the actual electricity use of the fogging system ($E_{C;Fog}$) as sensible cooling ($E_{C;Sen}$) when vents are opened for natural ventilation, which is calculated in KASPRO. Additionally, we consider that the conversion of natural gas into electricity use depends on the same conversion efficiency as heating, therefore $Q_H = E_H$. Electricity and light are not converted, therefore COP = 1.

The UAE-GH features a hybrid cooling system, where the electricity demand for latent and sensible cooling is determined by the heat pump, the heat exchanger + fans and the fogging system. Sensible and latent cooling in UAE are calculated by the aforementioned cooling loads, their respective energy requirement for the heat exchangers + fans ($E_{C;Fan}$), and the electricity use of the fogging system ($E_{C;Fog}$) according to the formulas:

$$E_{C;Lat} = \frac{Q_{C;Lat}}{COP} + \frac{Q_{C;Lat}}{Q_{C;Hex}} \cdot E_{C;Fan} \tag{6}$$

$$E_{C;Sen} = \frac{Q_{C;Ns} + Q_{C;Hex} - Q_{C;Lat}}{COP} + \frac{Q_{C;Hex} - Q_{C;Lat}}{Q_{C;Hex}} \cdot E_{C;Fan} + E_{C;Fog} \tag{7}$$

In order to determine the total electricity demand for plant factories ($E_{PF}$), we calculated the electricity demands for heating ($E_H$), dehumidification or latent cooling ($E_{C;Lat}$), and sensible cooling ($E_{C;Sen}$). Additionally, we calculated the energy required for powering ($E_{LED}$) and

**Table 3**
Coefficients of performance for the conversion of system loads in electric systems. These coefficients were determined using the Carnot efficiency of a heat pump, following the method presented by Meggers et al. (2012) and using temperatures weighted for corresponding load.

| | Heating | Dehumidification | Sensible cooling | LED cooling | (LED) Electric |
|---|---|---|---|---|---|
| SWE | 3.4 | 10.0[a] | 10.0[a] | 10.0[a] | 1 |
| NLD | 5.0 | 7.5 | 7.5 | 7.5 | 1 |
| UAE | 10.0[a] | 3.7 | 3.7 | 3.7 | 1 |

[a] The use of a heat pump would be inappropriate in this situation, since the outside temperature is adequate in using (air/air) heat exchangers for heating/cooling. In these cases the COP was set at 10.

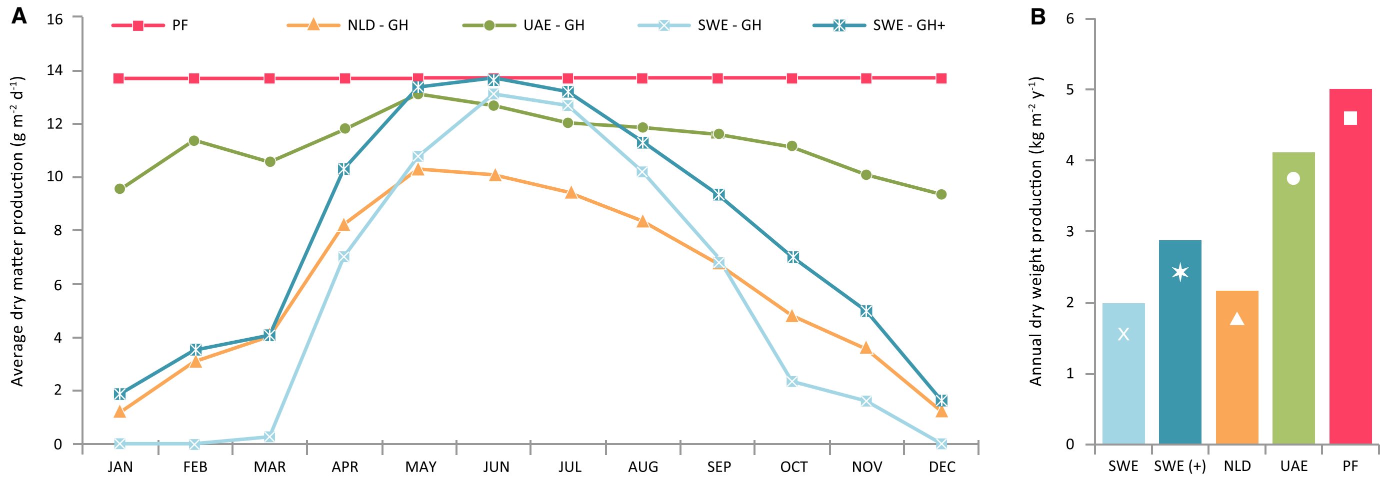


**Fig. 3.** Moving average of daily dry matter production ($g\,m^{-2}\,d^{-1}$) (A) and total annual dry weight production ($kg\,m^{-2}\,y^{-1}$) per cultivation area (B). Squares represent the plant factories, triangles represent greenhouses in NLD, circles represent greenhouses in the UAE, and crosses and stars represent greenhouses in SWE without and with artificial illumination, respectively.

cooling ($E_{C;LED}$) the LED fixtures. This is represented by the following formula:

$$E_{PF} = E_H + E_{C;Lat} + E_{C;Sen} + E_{C;LED} + E_{LED} \tag{8}$$

The calculation of total energy demand for greenhouses ($E_{GH}$) also includes total solar radiation. KASPRO calculates greenhouse transmissivity in relation to solar position. The radiation that is not transmitted ($E_{S;nTrans}$), is subdivided into reflection and absorption by greenhouse elements to account for the warming effect of the latter. The transmitted radiation is subdivided into photosynthetically active radiation ($E_{S;PAR}$) and near-infrared radiation ($E_{S;NIR}$) according to the formula:

$$E_{GH} = E_H + E_{C;Lat} + E_{C;Sen} + E_{LED} + E_{S;nTrans} + E_{S;PAR} + E_{S;NIR} \tag{9}$$

### 2.4.3. Water

All water expenditure ($W_{GH}$) has been taken up by the crop, as we assumed that there is no water loss from the irrigation system. Most water is transpired by the crop and subsequently extracted through natural ventilation ($W_{Air,Out}$), or condensed at the greenhouse cover ($W_{Con,Air}$) or the heat exchanger ($W_{Con,Hex}$). It is assumed that condensed water was retrieved, allowing for a loss of 10%. Finally, a small fraction is stored in the biomass of the crop ($W_{fw\text{-}dw}$). The water content in lettuce biomass can be estimated by making an assumption about the fixed dry matter content, for instance 7% (Koudela and Petříková, 2008; Gent, 2014). Water expenditure is given in the following formula:

$$W_{GH} = W_{FW-DW} + W_{Air;Out} + 0.1(W_{Con;Air} + W_{Con;Hex}) \tag{10}$$

In this model condensation on surfaces other than the greenhouse cover or the cooler is not retrieved but re-evaporated. The water used in the fogging system is calculated separately in the KASPRO model. Plant factories are designed as closed systems and do not include water loss resulting from exfiltration and ventilation. Therefore, total water use in plant factories is assumed to be the water content of the produce ($W_{fw\text{-}dw}$).

### 2.4.4. $CO_2$

In greenhouses, ventilation limits the $CO_2$ concentration that can be maintained; in practice a certain $CO_2$ concentration is selected (simulation setpoint: 800 ppm). The concentration that is attained is the result of the supply capacity and the ventilation rate. KASPRO uses the dosage and operational time of the $CO_2$ supply system to calculate the total amount of supplied $CO_2$. Similar to water vapour, $CO_2$ is considered not to exit plant factories; all supplied $CO_2$ is assimilated. Therefore, the total amount of supplied $CO_2$ in plant factories is calculated as twice the accumulated dry weight. This results from the weight loss in the transformation from $CO_2$ to carbohydrates (68%) and the fixation efficiency of $CO_2$ (approximately 70%) and an assumed harvest index of 1 (ratio of yield dry matter to total dry matter, see Section 2.2) for lettuce.

## 3. Results

The production and the use of water and $CO_2$ are quite similar in the three plant factories. Therefore we decided to specify and analyse only the results for the NLD-PF, unless stated differently. Results are normalised for cultivation area and for dry matter production.

The total dry matter production (Fig. 3) and the corresponding resource use were calculated for each lettuce production system at the three sites. A dry matter content of 7% results in a fresh weight production of approximately 31 $kg\,m^{-2}$ in greenhouses in NLD. This corresponds closely with the usual Dutch greenhouse production, as reported by Vermeulen (2014, p. 125). Fig. 4 illustrates the annual energetic loads in $MJ\,y^{-1}$, broken down into the energy use for LED lighting, the cooling of the LED lamps, sensible cooling, dehumidification and heating. Solar radiation is included in the calculation in order to illustrate the total energy requirement. The annual electricity requirement for all systems was assessed according to the method described in Section 2.4.2. The energetic efficiency of the systems was determined by normalising the energy requirement for dry weight production (Fig. 5). The use of water and $CO_2$ by each facility is illustrated in Figs. 6–8. Finally, a brief overview of the resource use efficiency of each system is given in Fig. 9.

## 4. Discussion

Fig. 3 shows the most obvious benefit of a plant factory compared with a greenhouse or open field production: it enables a high and uniform production year-round. The optimisation and uniformity of the interior climate of plant factories result in a production of dry matter

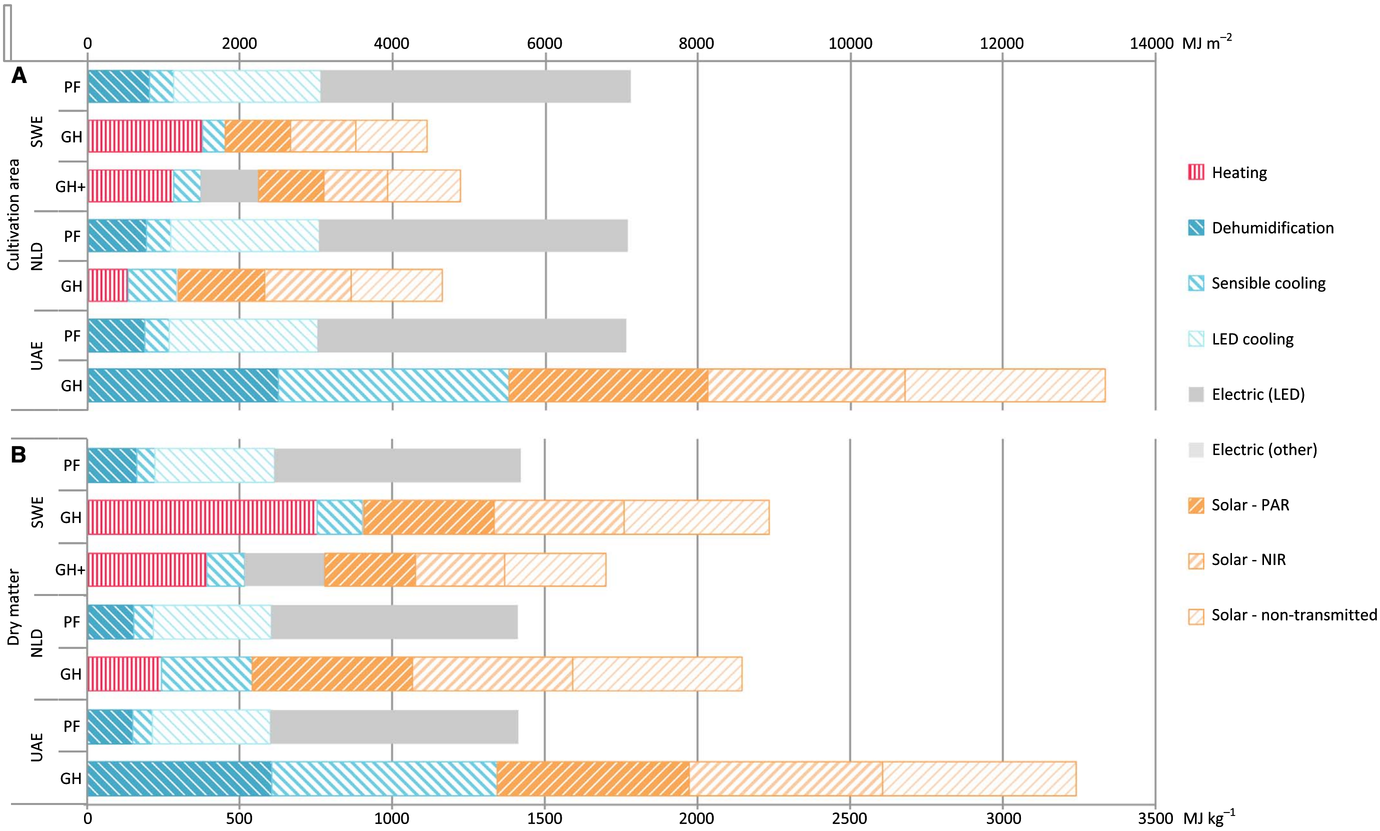


**Fig. 4.** Energy load of plant factories and greenhouses in UAE, NLD and SWE, normalised for cultivation area (MJ m$^{-2}$) (A) and for dry matter production (MJ kg$_{dw}$$^{-1}$) (B).

that is higher and more consistent than in greenhouses. The efficiency of this production, however, depends on a number of resources, as discussed below.

### 4.1. Energy use

Plant factories require a larger input of purchased energy than greenhouses for the production of lettuce. The energy efficiency of plant factories, however, is considerably higher. The calculated load of artificial illumination in plant factories exceeds all other loads for each facility at each location (Fig. 4). Other notably high energy loads are heating for NLD-GH and SWE-GH(+) and sensible/latent cooling for UAE-GH and all plant factories. In plant factories this cooling load results from the relatively high internal heat load from crop transpiration and the inefficiency of the LED fixtures.

The total system loads per cultivation area are greater in plant factories than in most greenhouses, even when taking solar energy into account (Fig. 4). The total amount of equivalent energy required for the production of dry matter in plant factories, however, is lower than in greenhouses at each location (Fig. 4). The semi-closed, transparent and conductive nature of the greenhouse design is responsible for this inefficient use of resources.

The greenhouse clearly excels with respect to the use of freely available solar energy. Greenhouses require less purchased energy than plant factories (Fig. 5). Compared with the dry matter production in greenhouses, the plant factory requires an additional input of 30 kWhe kg$^{-1}$ (+14%) for SWE-GH, 59 kWhe kg$^{-1}$ (+33%) for SWE-GH+, 176 kWhe kg$^{-1}$ (+251%) for NLD-GH and 158 kWhe kg$^{-1}$ (+142%) for UAE-GH (Fig. 9A). Direct use of solar energy has a greater impact on the total energy requirement than an efficient use of energy.

Presumably plant factories are more suitable than greenhouses for lettuce production at higher latitudes. This is illustrated by the fact that the energetic performance of SWE-GH+ considerably improves with artificial lighting. At even higher latitudes, heating is supposed to require more electricity than lighting. This supposition concurs with the idea that plant factories are effective in minimising electricity consumption in extremely dark/cold regions (Kozai, 2013b). However, the idea that plant factories may also minimise electricity consumption in hot and arid regions seems to be erroneous, as suggested by the energetic efficiency of facilities in UAE. Here, freely available solar energy saves more electricity than is needed for cooling purposes.

### 4.2. Other resources: water, $CO_2$ and land area

The viability of plant factories may depend on the efficient use of local resources; particularly water and land area may be scarce. At all three locations plant factories use these resources more efficiently than greenhouses.

The water use efficiency increases with lower ventilation requirements (Katsoulas et al., 2015). In this study we could confirm that (nearly) closed systems, such as UAE-GH and all plant factories, provide higher water use efficiencies than semi-open systems, such as NLD-GH and SWE-GH(+) (Figs. 6–7). The water use in closed systems is presumed to approach the water content of the produce (Section 2.4.3). When assuming a harvest index of 1.0 (Section 2.2), the plant factory could have a theoretical water use efficiency of 100% (Kozai, 2013a). Production in plant factories could reduce water use by 28% (UAE) to 95% (NLD) compared with greenhouses. Water use efficiency in

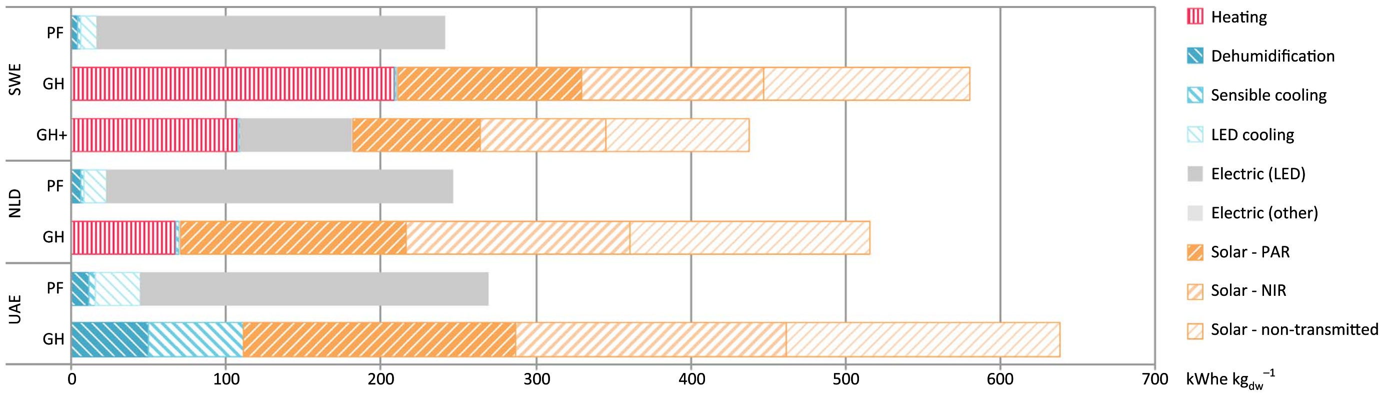


**Fig. 5.** Electricity use per kg lettuce dry matter production (kWhe kg$_{dw}^{-1}$) by end use. Electricity use has been calculated according to the methods described in Section 2.4.2.

relation to dry weight is demonstrated in Fig. 9C.

Similar to water, the use of $CO_2$ is strongly influenced by the ventilation requirements of the facility (Fig. 8). This is illustrated by SWE-GH where low temperatures during summer result in a lower requirement for natural ventilation compared with UAE-GH and NLD-GH. Concomitantly in SWE-GH a high retention rate and concentration of $CO_2$ is achieved, as well as an increased production. Production in plant factories could reduce $CO_2$ use by 67% (UAE) to 92% (NLD) compared with greenhouses. $CO_2$ use efficiency in relation to dry weight is illustrated in Fig. 9B.

Finally, the land area can also be considered as a resource. Stacking production layers implies a linear increase in the production capacity. In this study we simulated five layers, but more are possible. In closed systems additional production layers should not affect the resource use efficiency. A high production density could overload the climatisation system, thereby decreasing efficiency and increasing energy expenditure. The densification of production, however, becomes more important in view of the variations in price and availability of land.

### 4.3. Relevance of the assumptions

The production in each facility depends on interior climate, cultivar selection, crop production system and construction design. Production and energetic efficiency (calculations) could be improved by selecting a different growth model and by optimising the climate setpoints. In this study, the dry matter production of lettuce at higher temperatures (UAE-GH and PFs) was presumably underestimated by the Van Henten (1994) model due to a decrease in productivity at higher temperatures (Section 2.2). Additionally, we have not comprehensively optimised the climate setpoints with regard to maximum production at each location and for each typology. According to the model, the net dry matter production in plant factories could be increased by approximately 62% by lowering the production temperature to 19 °C. As a consequence, the cooling requirements would increase. Higher temperature setpoints for greenhouses in colder climates could also raise the production, but this would inevitably lead to higher heating requirements. In addition to temperature, the optimisation of intensity, composition and duration of lighting could improve lettuce production.

Production and energetic efficiency could be further optimised by the design of the crop production system and facility construction. In this study crop production systems were not designed for optimal spacing and cultivation intensity, as the Van Henten (1994) model does not include transplanting or respacing (Section 2.2). The total amount of required cultivation area, intensity of cultivation and general production schedule should be improved by continuous or discontinuous spacing (Seginer and Ioslovich, 1999). In this study we did not vary the construction design of the greenhouses and plant factories. In particular the performance of greenhouses could be improved by adjusting the design to each location. For instance, the use of double-layer covers or additional movable curtains could reduce the heating requirement by

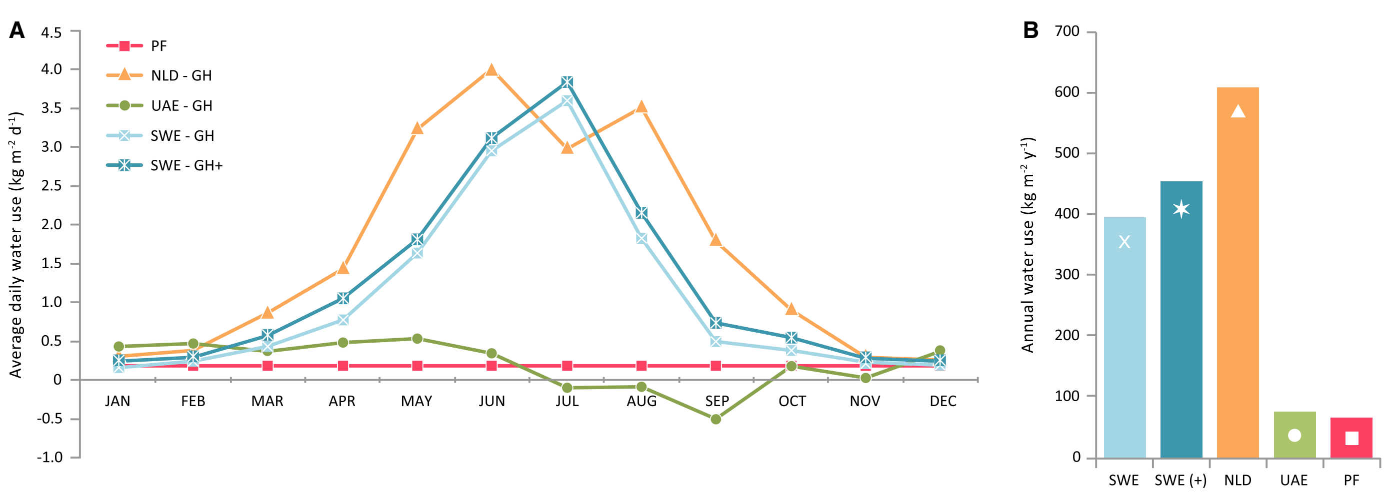


**Fig. 6.** Average daily water use (kg m$^{-2}$ d$^{-1}$) (A) and total annual water use per cultivation area (kg m$^{-2}$ y$^{-1}$) in plant factories and greenhouses (B). The negative values of UAE in summertime can be explained by the fact that the calculations include the influence of infiltration of water vapour. During the summer months the absolute vapour content of air is higher outside the greenhouse. This results in water vapour infiltrating the facility and consequently being condensed and retrieved.

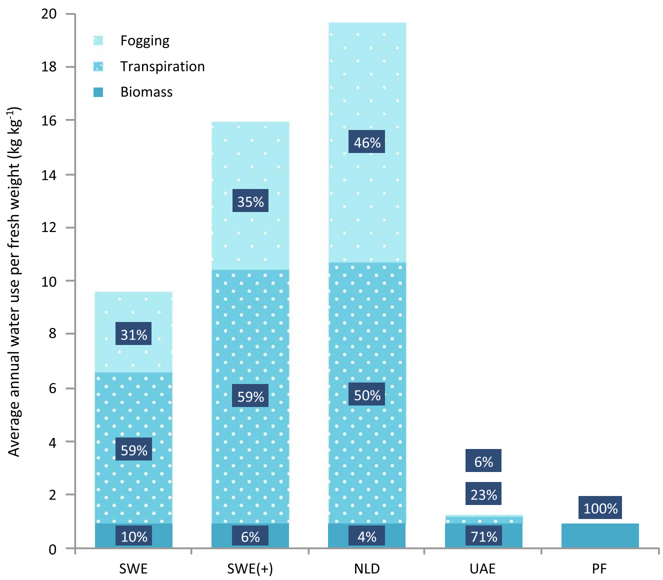


**Fig. 7.** Average annual water use per kg of fresh weight (kg $kg^{-1}$), divided for biomass and sources of water vapour. A dry matter content of 7% has been assumed throughout this study. The plant factory displays a theoretical water use efficiency of 1 to 1 (Kozai, 2013a).

almost half in SWE-GH and NLD-GH (e.g. Kempkes, 2017).

In summary we are aware of the uncertainty that ensues from our assumptions. Uniformity in processing the data, however, allows for a more straightforward interpretation without significantly altering the main outcomes of this study. Presumably a minor effect on these outcomes can be achieved by selecting different lettuce models, hardware and/or climate setpoints.

In plant factories the predominance of artificial illumination in the total energy balance and the high total energy requirement are consistent with data from a wide range of production climates (Nishimura et al., 2001; Tong et al., 2013; Harbick and Albright, 2016). These issues are usually addressed by the technological advancement of LED systems and the integration of photovoltaic cells.

Indeed, the feasibility of plant factories largely depends on artificial illumination and its efficiency. When taking SWE-PF as an example, an increase of LED efficiency to 59% (Red:Blue = 80:20, 10.70 mol $kWhe^{-1}$) could reduce electricity use for the production of dry matter to 210 kWhe $kg_{dw}^{-1}$, which is lower than in SWE-GH. When we consider a theoretical LED efficiency of 100% (Red:Blue = 80:20, 18.15 mol $kWhe^{-1}$) the electricity use in NLD-PF and UAE-PF could be decreased to 132 kWhe $kg_{dw}^{-1}$ and 124 kWhe $kg_{dw}^{-1}$ respectively. The electricity use in the latter plant factories, however, would still be higher than in NLD-GH (70 kWhe $kg_{dw}^{-1}$) and UAE-GH (111 kWhe $kg_{dw}^{-1}$). The technological advancement in LED efficiency is of paramount importance, but presumably this is not sufficient to ensure the feasibility of plant factories.

Photovoltaic cells could be used to supply plant factories with renewable electricity. Modern monocrystalline silicon photovoltaic cells are able to reach efficiencies as high as 23% (Green et al., 2015). In practice, however, the efficiency of photovoltaic arrays does not exceed 17% (Tyagi et al., 2013). When taking the roof of NLD-PF as an example (global solar radiation of 3.54 GJ $m^{-2}$ $y^{-1}$ (KNMI, 2014), a photovoltaic array of 10,000 $m^2$ with an efficiency of 17% would be able to produce 1.67 GWh $y^{-1}$. This equals 2.71% of the plant factory's total annual electricity requirement. For lighting purposes direct solar energy is more efficient than artificial illumination powered by photovoltaic arrays. This can be illustrated by successively calculating the current efficiencies of photovoltaic cells (17%) and LED systems (52%, Section 2.3.3).

## 5. Outlook

At all three locations the greenhouse is more efficient in terms of purchased energy. It may be surprising that the benefits of solar energy exceed the need for climatisation even in the harsh environments of Kiruna and Abu Dhabi. This study demonstrates that the turnover point, where plant factories may be more energy efficient than greenhouses, lies in even more extreme environments. However, greenhouses in our most extreme locations (Kiruna and Abu Dhabi) were not viable without incorporating features of plant factories, such as artificial lighting and active cooling, respectively. This suggests that there is not a specific turnover point. Instead there is probably a gradual shift from a nearly natural to a fully controlled interior production climate. A shift in applicability of each typology is closely related to the energy use efficiency in greenhouses versus plant factories. The ratio of required input of energy can be estimated on the basis of Köppen-Geiger climate zones and latitude. This may determine the suitability of plant factories compared with greenhouses (Fig. 10).

In reality, the viability of the system as a whole does not solely depend on energetic performance. The efficiency of production and climatisation systems is directly related to the availability of resources. At locations with scarce resources plant factories offer opportunities by assuring an efficient use of water and $CO_2$ as well as a high production density (Fig. 10).

Additional marketing advantages could also offset higher operational costs. A high and constant level of production allows the

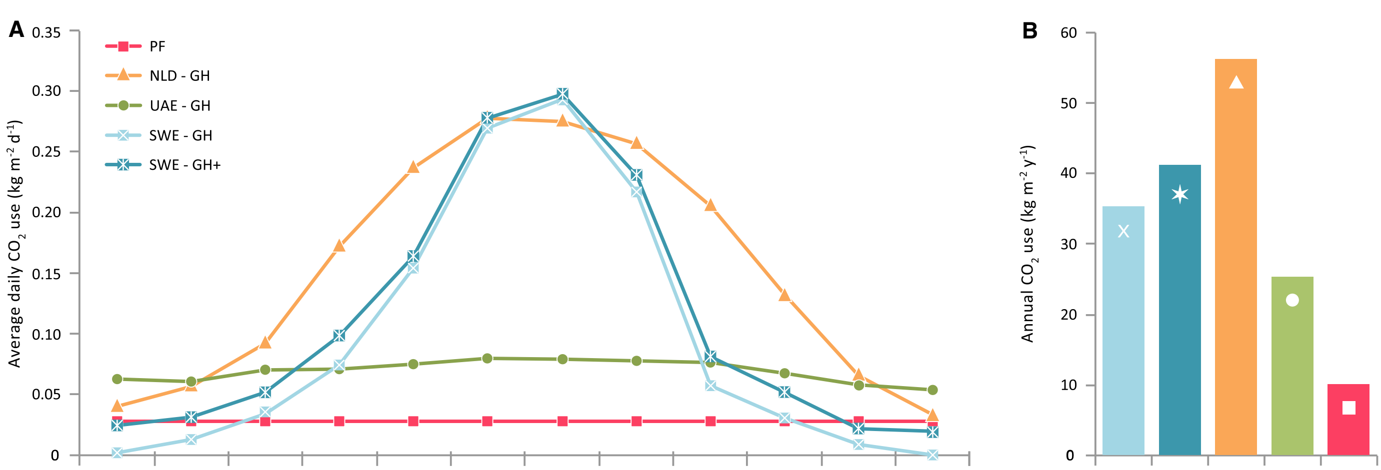


**Fig. 8.** Average daily $CO_2$ use (kg $m^{-2}$ $d^{-1}$) (A) and total annual $CO_2$ use (kg $m^{-2}$ $y^{-1}$) per cultivation area in plant factories and greenhouses (B).

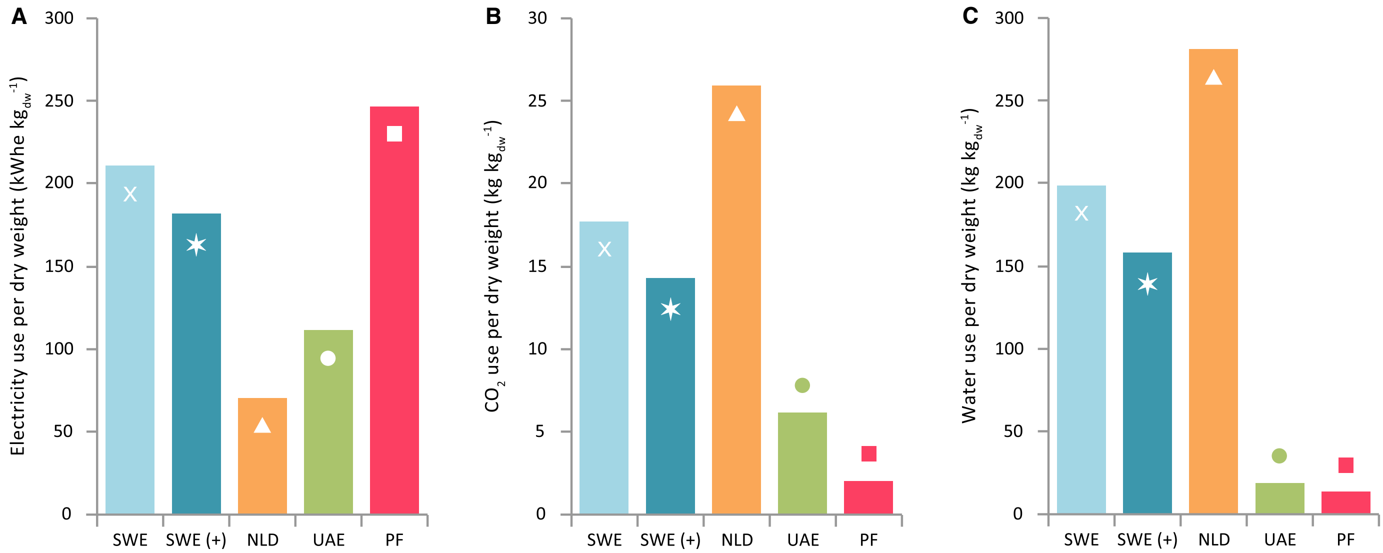


**Fig. 9.** Resource use for electricity (A), $CO_2$ (B) and water (C) of the plant factory (PF) and greenhouses (SWE, SWE(+), NLD and UAE), normalised for total dry matter production ($kg_{dw}$).

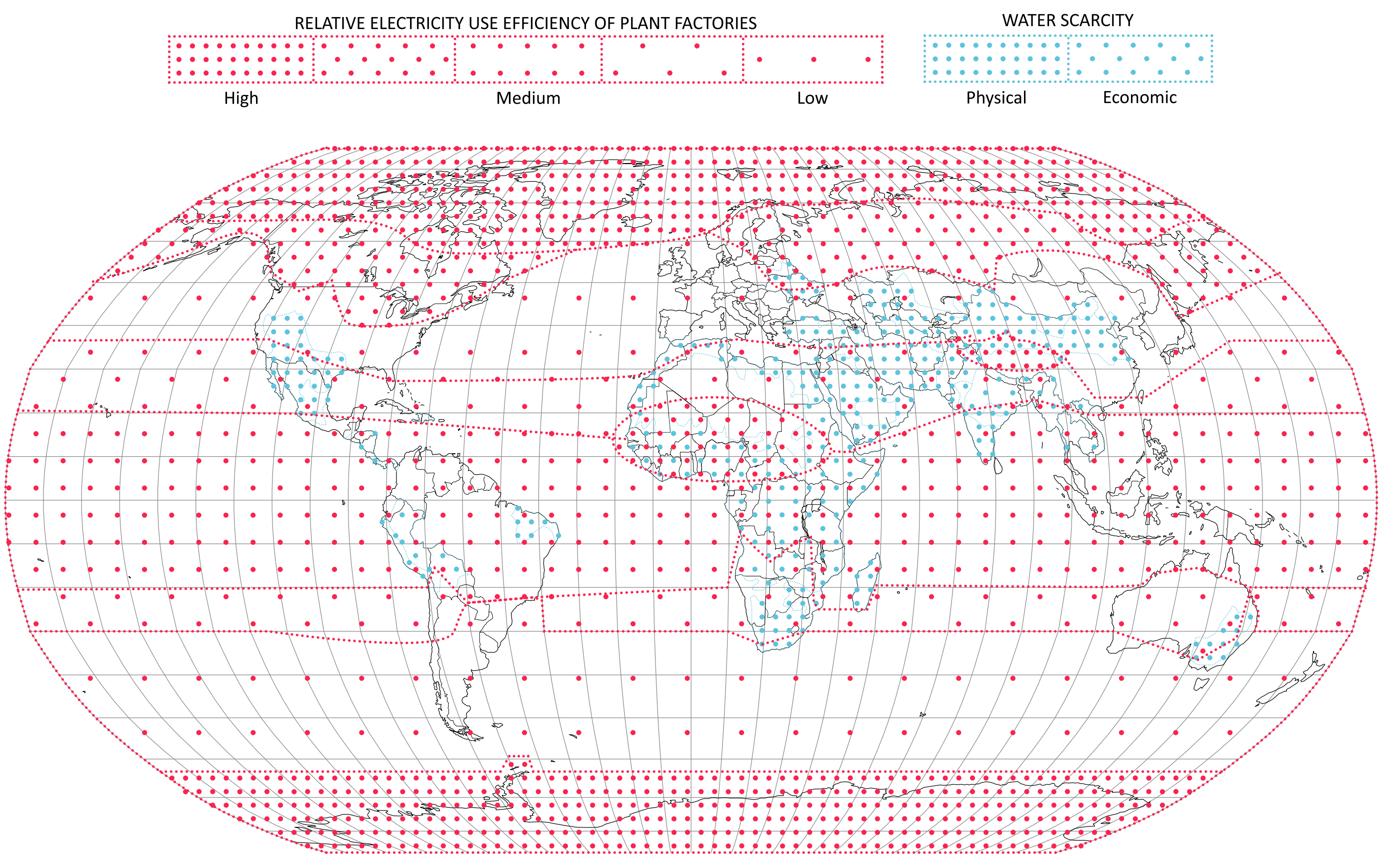


**Fig. 10.** Estimation of the advantages of plant factories versus greenhouses based on relative electricity use efficiency (red) and water scarcity (blue). Water scarcity is subdivided into (approaching) physical and economic scarcity (UN, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

customer to reduce the number of contracted producers and to avoid the risk of asynchronous or insufficient supply. Moreover, the closed production environment of plant factories minimises the risk of pathogen infiltration and the need for protective chemicals. These side effects can increase the market value of the crop.

## 6. Concluding remarks

This study investigates the energetic requirements for the production of lettuce in different climate regions within either plant factories or greenhouses. The input and output were calculated, analysed and compared with respect to diverse latitudes and climates: Northern Sweden, the Netherlands and the United Arab Emirates. The results provide insight into the influence of the exterior climate on the production requirements and the performance of greenhouses and plant factories.

The outcome that plant factories would require a higher (purchased) energy input due to artificial lighting might have been foreseen. This study, however, offers detailed insights into the different interior and exterior exchanges and their influence on the production and the energy balance. Plant factories may offer many other advantages, such as a high retention of resources, uniformity of interior climate and density and quality of production. The disadvantage remains the high energetic demand due to the need for artificial lighting.

To forgo solar energy has a negative impact on the economic viability of a facility. This analysis enabled us to quantify this effect and determine the required offset. Additionally, it gave an indication of the productivity of various resources. Future research could use this approach for more comprehensive analyses and calculations on the financial and logistic viability of urban agricultural production in closed systems.

**Acknowledgements**

This work was supported jointly by the EU-H2020 project "Ground Demonstration of Plant Cultivation Technologies and Operation in Space for Safe Food Production on-board ISS and Future Human Space Exploration Vehicles and Planetary Outposts" (EDEN-ISS, grant 636501) and by the Dutch Top Sector Tuinbouw & Uitgangsmaterialen (EU-2016-01). However, no endorsement of the results and conclusions by the European Commission or by the Dutch Ministry of Economic Affairs and Climate Policy is hereby implied. Thanks are due to Willem van der Spoel for his expert examination of the DesignBuilder model.

## Appendix A. List of symbols, subscripts and abbreviations

| Symbol | Description | Unit |
|---|---|---|
| $c_g$ | Energy conversion efficiency of natural gas | MJ m$^{-3}$ |
| $c_w$ | Heat capacity of water | J g$^{-1}$ |
| *COP* | Coefficient of performance | [−] |
| *E* | Electricity use | kWhe |
| $G_H$ | Natural gas use for heating | m$^3$ |
| *LAI* | Active leaf area index | $m^2_{leaf}\ m^{-2}_{soil}$ |
| *PPFD* | Photosynthetic photon flux density | μmol m$^{-2}$ s$^{-1}$ |
| *Q* | Energetic load | J |
| *RH* | Relative humidity | % |
| *W* | Water use | kg |
| $(\ )_{Air;Out}$ | Exiting the greenhouse through ventilation | |
| $(\ )_{C;Lat}$ | Latent cooling | |
| $(\ )_{C;Sen}$ | Sensible cooling | |
| $(\ )_{C;Fan}$ | Air circulation by fan for cooling | |
| $(\ )_{C;Hex}$ | Cooling by heat exchanger | |
| $(\ )_{C;LED}$ | Cooling of the LED fixture | |
| $(\ )_{Con;Air}$ | Condensed on greenhouse cover | |
| $(\ )_{Con;Hex}$ | Condensed by heat exchanger | |
| $(\ )_{dw}$ | Dry weight | |
| $(\ )_{fw\text{-}dw}$ | Water content of biomass | |
| $(\ )_{GH}$ | Greenhouse | |
| $(\ )_{H}$ | Heating | |
| $(\ )_{LED}$ | LED | |
| $(\ )_{PF}$ | Plant factory | |
| $(\ )_{S;nTrans}$ | Non-transmitted solar radiation | |
| $(\ )_{S;PAR}$ | Photosynthetically active solar radiation entering the facility | |
| $(\ )_{S;NIR}$ | Near-infrared solar radiation | |
| *NLD* | The Netherlands | |
| *SWE* | Sweden | |
| *UAE* | The United Arab Emirates | |
| *-GH* | Greenhouse without artificial illumination | |
| *-GH+* | Greenhouse with artificial illumination | |
| *-PF* | Plant factory | |

**Appendix B. Optical properties and average transmissivity of the combination of a standard glass cover and the Venlo greenhouse structure. The table shows the direct transmission values for a specific solar azimuth and elevation. Additionally, this table lists the hemispherical greenhouse transmission (tr_diff), specific heat of glass (cp) and type of cover (type). These values can be used to calculate the thermal exchange between the greenhouse and the surrounding climate.**

| | | **Diffuse transmission** | | | | tr_diff: | | 0.755 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Direct** | **Transmission** | **Specific heat per m material** | | | | cp: | | 8736 | | | | | | | | |
| **Azimuth** | **\Elevation** | **Single or double cover** | | | | Type: | | Single | | | | | | | | |
| **0** | **0** | **2** | **4** | **6** | **8** | **10** | **15** | **20** | **25** | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| **0** | **0** | 0 | 0.060 | 0.136 | 0.212 | 0.284 | 0.437 | 0.553 | 0.635 | 0.694 | 0.763 | 0.799 | 0.819 | 0.832 | 0.842 | 0.850 |
| **5** | **0** | 0.020 | 0.082 | 0.153 | 0.220 | 0.288 | 0.438 | 0.551 | 0.634 | 0.692 | 0.760 | 0.797 | 0.818 | 0.831 | 0.841 | 0.850 |
| **10** | **0** | 0.026 | 0.131 | 0.204 | 0.275 | 0.327 | 0.445 | 0.551 | 0.632 | 0.690 | 0.760 | 0.798 | 0.817 | 0.831 | 0.841 | 0.850 |
| **15** | **0** | 0.030 | 0.149 | 0.241 | 0.318 | 0.381 | 0.477 | 0.556 | 0.630 | 0.687 | 0.759 | 0.796 | 0.818 | 0.830 | 0.841 | 0.850 |
| **20** | **0** | 0.032 | 0.162 | 0.273 | 0.351 | 0.415 | 0.525 | 0.577 | 0.632 | 0.685 | 0.756 | 0.796 | 0.817 | 0.829 | 0.840 | 0.850 |
| **25** | **0** | 0.033 | 0.169 | 0.289 | 0.381 | 0.440 | 0.553 | 0.614 | 0.643 | 0.685 | 0.754 | 0.794 | 0.816 | 0.832 | 0.840 | 0.850 |
| **30** | **0** | 0.041 | 0.172 | 0.300 | 0.394 | 0.476 | 0.573 | 0.641 | 0.670 | 0.690 | 0.752 | 0.793 | 0.817 | 0.831 | 0.840 | 0.850 |
| **35** | **0** | 0.033 | 0.192 | 0.307 | 0.405 | 0.477 | 0.588 | 0.655 | 0.694 | 0.704 | 0.751 | 0.792 | 0.816 | 0.831 | 0.840 | 0.850 |
| **40** | **0** | 0.045 | 0.182 | 0.313 | 0.414 | 0.488 | 0.601 | 0.666 | 0.709 | 0.724 | 0.751 | 0.791 | 0.816 | 0.831 | 0.840 | 0.850 |
| **45** | **0** | 0.030 | 0.186 | 0.317 | 0.421 | 0.497 | 0.629 | 0.675 | 0.716 | 0.740 | 0.752 | 0.790 | 0.816 | 0.831 | 0.840 | 0.850 |
| **50** | **0** | 0.026 | 0.190 | 0.322 | 0.428 | 0.505 | 0.639 | 0.683 | 0.723 | 0.750 | 0.756 | 0.790 | 0.816 | 0.833 | 0.843 | 0.850 |
| **55** | **0** | 0.048 | 0.194 | 0.356 | 0.435 | 0.513 | 0.630 | 0.691 | 0.729 | 0.756 | 0.763 | 0.791 | 0.816 | 0.833 | 0.844 | 0.850 |
| **60** | **0** | 0.017 | 0.213 | 0.368 | 0.443 | 0.521 | 0.638 | 0.699 | 0.735 | 0.761 | 0.773 | 0.791 | 0.817 | 0.833 | 0.844 | 0.850 |
| **65** | **0** | 0.011 | 0.242 | 0.379 | 0.451 | 0.529 | 0.646 | 0.721 | 0.741 | 0.766 | 0.783 | 0.793 | 0.817 | 0.834 | 0.844 | 0.850 |
| **70** | **0** | 0.005 | 0.254 | 0.362 | 0.461 | 0.539 | 0.655 | 0.732 | 0.748 | 0.771 | 0.791 | 0.794 | 0.818 | 0.835 | 0.845 | 0.850 |
| **75** | **0** | 0.044 | 0.267 | 0.370 | 0.471 | 0.549 | 0.664 | 0.741 | 0.754 | 0.777 | 0.798 | 0.797 | 0.820 | 0.836 | 0.845 | 0.850 |
| **80** | **0** | 0.055 | 0.282 | 0.383 | 0.484 | 0.561 | 0.673 | 0.749 | 0.761 | 0.782 | 0.804 | 0.799 | 0.821 | 0.837 | 0.845 | 0.850 |
| **85** | **0** | 0.054 | 0.287 | 0.390 | 0.492 | 0.571 | 0.684 | 0.758 | 0.768 | 0.788 | 0.809 | 0.802 | 0.823 | 0.838 | 0.846 | 0.850 |
| **90** | **0** | 0.055 | 0.291 | 0.393 | 0.495 | 0.574 | 0.688 | 0.766 | 0.775 | 0.794 | 0.814 | 0.805 | 0.825 | 0.839 | 0.847 | 0.850 |

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