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Life cycle climate performance of urban plant factory *versus* rural greenhouse under China's power-grid decarbonization: considering short-lived methane and nitrous oxide emissions

Yunlai Cheng[1], Guobao Song[1], Xiaoyang Liu[1], Laura Batlle-Bayer[2], Pere Fullana-i-Palmer[2]

[1]Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, Liaoning, China.
[2]UNESCO Chair in Life Cycle and Climate Change ESCI-UPF, Universitat Pompeu Fabra, Barcelona 08003, Spain.

Correspondence to: Dr. Guobao Song, Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), School of Environmental Science and Technology, Dalian University of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian 116024, Liaoning, China. E-mail: gb.song@dlut.edu.cn

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Abstract

Plant factories can potentially enhance the climate resilience of urban vegetable production by reducing the losses from climate hazards but generate high climate burdens - due to consuming carbon-intensive power generated by coal combustion with upstream methane emissions - unlike rural traditional sunlight greenhouses with nitrous oxide emissions. Here, we compared the life cycle Global Warming Potential (GWP) and Technical Warming Potential (TWP) metrics of lettuce production by plant factory and greenhouse, and explored the effect of power grid decarbonization on the climate performance of the cultivations. Results show that in the baseline scenario using the southern Chinese grid, the 100-year GWP of plant factory cultivation (14.9 $kgCO_2e\ kg^{-1}$) is over 50 times higher than that of the greenhouse (0.27 $kgCO_2e\ kg^{-1}$). The nitrous oxide emissions contribute 14% to the GWP of greenhouse, while methane contributes 16% to that of plant factories, which can be reduced to ~4% under a high grid decarbonization scenario in 2050. Electricity consumption (fertilizer and polyethylene film applications) shares 43%-99% (80%-89%) of the GWP of plant factory (greenhouse) cultivations. Grid decarbonization decreases the TWP metrics over time, meaning a rising climate advantage for plant factories. However, plant factories still fail to compete with greenhouses in mitigating climate change (with TWP ranging from 5-66), except if hydropower were fully deployed. Our findings add knowledge about climate-friendly and resilient vegetable supplies under China's grid decarbonization efforts.

Keywords: Climate resilience, plant factory, crystallinity of COF, sunlight greenhouse, global warming potential, methane, nitrous oxide

INTRODUCTION

Plant factories, as indoor infrastructures for plants growing under a controlled environment, can increase the climate resilience of vegetable production[1,2]. However, the climatic performances of plant factories differ from traditional sunlight greenhouses. Traditional greenhouses produce vegetables relying on nitrogen fertilizers, with the corresponding nitrous oxide (N_2O) emissions[3,4], while plant factories primarily rely on artificial illumination, consuming power[1,2], possibly with upstream methane (CH_4) emissions. For example, China's upstream coal mining to generate power was recognized as a major global methane emitter[5,6]. Short-lived methane and nitrous oxide are more potent than carbon dioxide in heating climate and have been responsible for a 0.5 and 0.1 °C warming in the past decade, respectively[7]. Neglecting the warming effect of the short-lived climate forcers may offset the intended benefits of shifting toward low-carbon technologies[8,9]. Thus, despite reducing fertilizer inputs, plant factory cultivations on coal-fired power likely raise the climate burdens of vegetable production by replacing greenhouses.

Plant factories show significant promise in China since half of the world's vegetables are grown there[3]. Recently, China released an Action Plan for Peaking Carbon Dioxide Emission before 2030, promoting power-grid decarbonization by coal phase-out policy[10]. Therefore, we ask: Can grid decarbonization improve plant factory's climate performance compared to greenhouses? This question is complicated by the short-lived methane and nitrous oxide emissions. The reason is that the commonly used global warming potential (GWP), like in prior Life Cycle Assessment (LCA)-based studies[11-13], allows for comparing the GHGs (or carbon footprint) between technologies at a fixed time horizon, but fails to evaluate the dynamically cumulative radiative forcing of multiple GHGs due to the varied atmospheric lifetimes[14]. However, the technological warming potential (TWP) method overcomes this barrier[14].

Here, we applied the LCA-based TWP method[8,14] to compare the climate performances of producing lettuce in a plant factory with artificial light and in a traditional sunlight greenhouse. Additionally, we extensively reviewed China's grid decarbonization pathways to set the scenarios and tested their effects on the TWP metrics (see Methods and data). The novelty of this study lies in two aspects: For one thing, compared with previous studies on the climate performance of plant factories, this paper uniquely considers the contribution of non-CO_2 gases to climate impacts from the temporal dimension; for another, this study illustrates the climate feasibility of plant factories based on the context of electricity decarbonization in China. Thus, this study fills the knowledge gap of the previously neglected effect of grid decarbonization on the climate performance of newly soaring plant factories, especially when short-lived methane and nitrous oxide were highlighted.

METHODS AND DATA

Life cycle assessment of lettuce cultivation

Referring to the ISO14040 (2006)[15], LCA method assesses the climate burdens of a product through four steps, i.e., objective and system boundary definition, inventory analysis, environmental impact assessment, and result interpretation. The attributional method (JRC-IEA, 2010)[16] was selected in this study because our comparison targeted the average impact instead of the marginal influence[17]. The objective of the LCA modeling was to quantitatively assess and compare the climate loads of two lettuce production technologies (traditional sunlight greenhouse and artificial light plant factory). The sunlight greenhouse here refers to the single-span, east-west oriented greenhouse that is widely used in China. The sunlight greenhouse is not heated but fully relies on sunlight and outer thermal screens in the winter to ensure a suitable temperature for plant growth. Agricultural machinery was excluded from the analysis to simplify the LCA models and reduce the uncertainties.

The functional unit of the LCA model was defined as the production of 1 kg of fresh lettuce. The system boundary was defined as the cradle-to-farm gate [Figure 1]. The cultivating process includes sowing, seedling raising, planting (process 1), and management and harvesting (process 2). Inputs of raw materials, electricity, water, fertilizers, and related nitrogen oxide emissions were considered. We excluded the climate burdens of infrastructure construction and equipment maintenance of greenhouse and plant factory cultivation from the scope of this study due to their long lifetime.

The traditional sunlight greenhouse is located in the middle and lower reaches of the Yangzi River, covering an area of approximately 667 m^2 and produces about 4 tons of lettuce annually by four rounds of cultivation. Chemical and organic fertilizers are applied to meet the nutritional requirements of the lettuce growth. The greenhouse depends on sunlight insulated by polyethylene film, without using artificial illumination as a supplementary light source. The plant factory with artificial light is owned by Anhui SANANBIO Biotechnology Co., Ltd, located in Luan City of Anhui Province. The plant factory has an area of about 260,000 m^2 and produces lettuce annually. The plant factory has a fully controllable environment, using LED spectrum technology and nutrient solution con uration to precisely control the light, water, and nutrients required for lettuce.

Notably, the two cultivation systems are with such disproportionate production areas. This is because a sunlight greenhouse can be operated individually per square foot, while a plant factory is a more collaborative system, where multiple factors such as power control system and nutrient delivery system, *etc.*, need to be considered collectively as an entire system. All inputs of the two disproportionate cultivation systems were standardized into the same functional unit to produce 1 kg of fresh lettuce for comparison purposes.

Life cycle inventory

We built the LCA model using OpenLCA software. The background data mainly came from the dataset of ecoinvent, facing challenges. Thus, when building flows in each process, we followed the principles below. Firstly, flows of materials, energy, and auxiliary were directly used if they were available in the background Ecoinvent database. Otherwise, similar materials were used as alternatives. For example, we used ammonium hydrogen phosphate and magnesium oxide to replace ammonium phosphate and magnesium nitrate[18,19], respectively, to add the flows of the nutrient solution of plant factory cultivations. This substitution unavoidably introduced uncertainties, however, which were negligible since the mass of the substituted substance was much less than 5% of the total inputs.

For traditional greenhouse cultivation, the foreground data include the seed, water, fertilizer, and auxiliary materials (See Supplementary Table 1 in the Supplementary Information for the details). Nitrogen fertilizer enters the soil to generate nitrate nitrogen through nitrification, and nitrate nitrogen then enters the anaerobic environment to release N_2O and other gases through denitrification. Notably, the use of nitrogenous fertilizers produces nitrous oxide with uncertainties. Therefore, when quantifying the nitrous flow in developing LCA models, we used different emission coefficients of nitrous oxide by referring to three previous investigations of Hergoualc'h *et al.* (2019); Wang *et al.* (2018), and Yue *et al.* (2019)[20-22]. Supplementary Table 2 gives details.

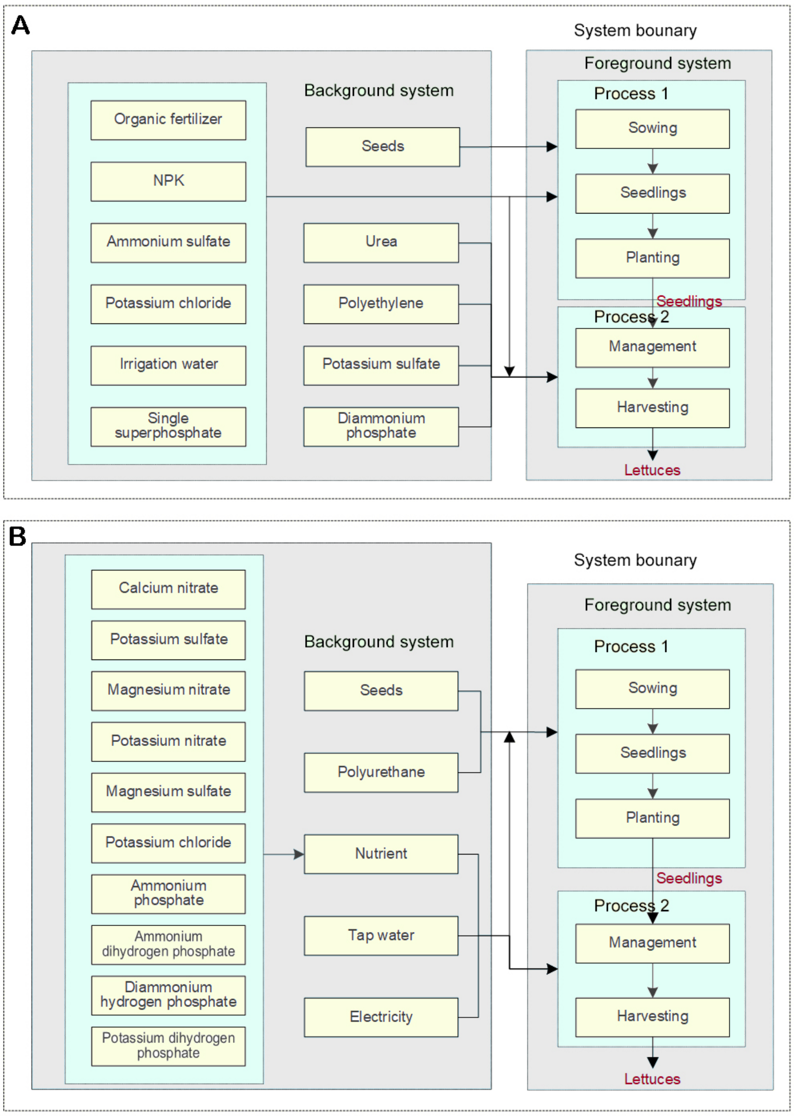

Figure 1. Diagrams of the system boundaries, processes and inputs-outputs for the life cycle analysis of one kilogram of fresh lettuce produced in the two infrastructures: (A) Traditional sunlight greenhouse and (B) plant factory with artificial light.

For the plant factory cultivation, the foreground data mainly came from the official environmental impact report of SANANBIO enterprises. However, this report fails to cover the data on electricity consumption. Thus, to ensure the robustness of our LCA model, we obtained electricity consumption data by reviewing a total of 15 investigations on plant factory cultivations across economies of China, Japan, the United States, Germany, the Netherlands, Sweden, and the United Arab Emirates [Supplementary Figure 1]. All reviewed data on power consumption and materials and energy inputs for the plant factory cultivation system were standardized into one kilogram (See Supplementary Tables 3 and 4). The average electricity consumption and uncertainties were used to improve the robustness of our LCA models.

Sensitivity analysis and uncertainties

Plant factories and greenhouses show different inputs of raw materials and resources into lettuce cultivation. We conducted the sensitivity analysis to quantitatively identify the key influential factors affecting the climate performance of the lettuce cultivations[23]. During sensitivity analysis, we set deviations of the target variable as ± 5% and ± 20%, respectively, while keeping other input parameters as constants or unchanged. The results of sensitivity analysis for the two lettuce cultivation systems are presented in Section "Sensitivity analysis for LCA models". Uncertainties in building the LCA model source from background and foreground data, such as electricity inputs and nitrous oxide emissions. Referring to the IPCC Guidelines for National Greenhouse Gas Inventories[24], we conducted the Monte Carlo simulation by defining the probability as a triangle distribution for random sampling, which is built in the OpenLCA software. Thus, uncertainties from multiple parameters were then propagated, accumulated, and quantified.

Scenario analysis

We developed the LCA models using electricity from China's Southern Grid as a baseline. Then, we examined the climate performances of plant factory cultivations by using seven pure power sources: coal (P1), natural gas (P2), oil (P3), solar (P4), wind (P5), nuclear (P6), and hydropower (P7). Additionally, considering China's grid transition for decarbonization, we also reviewed 64 grid decarbonization pathways from openly published literature and official reports [Supplementary Table 5]. Accordingly, from 2025 to 2050, coal-fired power generation will decline from 60% to 38%, while the share of wind and solar power will rise and reach 80% of the total electricity sources [Supplementary Table 6]. According to the percentage of coal-fired power in China's grid, we generated 12 low and high decarbonization scenarios of China's future power grid by cluster analysis, which were further used as inputs to LCA models to examine the climate performance of plant factory cultivation under Chinese grid decarbonization. These results are presented in Section "Grid decarbonization effect on plant factory's performance".

Technology warming potential

Based on the definition of global warming potential (GWP; Eq. 1), Alvarez *et al.* (2012) proposed the method of technology warming potentials (TWP) to quantitatively compare the relative cumulative forcing generated by alternative technologies by considering the leakage of short-lived methane[14]. Referring to Alvarez *et al.* (2012), we evaluated CH_4-focused TWP (Eq.2) and extended its scope to cover N_2O, on which the relative climate performance of plant factories and greenhouse cultivations were compared (Eq. 3)[14].

$$GWP_i = \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_{CO_2}(t)\,dt} \tag{1}$$

where TH represents the time horizon (year). $RF_i(t)$ and $RF_{CO_2}(t)$ represent the radiative forcing generated by the instantaneous emission of 1 kg GHG i and CO_2, respectively.

$$TWP_{\mathrm{CH4}}(t) = \frac{\sum_{i=1}^{2}\left[E_{\mathrm{P},i} * TRF_i(t)\right]}{\sum_{i=1}^{2}\left[E_{\mathrm{G},i} * TRF_i(t)\right]} \tag{2}$$

$$TWP_{\mathrm{CH4+N2O}}(t) = \frac{\sum_{i=1}^{3}\left[E_{\mathrm{P},i} * TRF_i(t)\right]}{\sum_{i=1}^{3}\left[E_{\mathrm{G},i} * TRF_i(t)\right]} \tag{3}$$

where $E_{\mathrm{P},i}$ and $E_{\mathrm{G},i}$ represent the emission of GHG i (i = 1-3 indexes CO_2, CH_4 , and N_2O, respectively). $TRF_i(t)$ represents the total radiative forcing of GHG i in year t, derived as follows.

Assuming the impulse emissions of GHG i at t_{E}, the cumulative radiative forcing CRF (t) produced between t_{E} and t year is given in Eq. 4. If GHG i is emitted continuously at a unit rate (1 kg year^{-1}) at $t = 0$, then $TRF_{\mathrm{i}}(t)$ after the year t is calculated as in Eq. 5 (W year m^{-2} kg^{-1}).

$$CRF_i(t) \equiv \int_{t_E}^{t} RE_i f_i(x, t_E)\, dt \tag{4}$$

$$TRF_i(t) \equiv \int_0^t \int_{t_E}^{t} RE_i f_i(x, t_E)\, dt dt_E \tag{5}$$

where $f_i(x,t_E)$ represents the mass of gas i remaining in the atmosphere after t years (Eqs. 6 and 7). RE_i represents the radiative efficiency (W m^{-2} kg^{-1}), i.e., the instantaneous radiative forcing to the earth's surface per unit mass of greenhouse gas I, which can be expressed as the times of the CO_2 reference gas[25]. Supplementary Table 7 gives details.

The exponential decay function of CH_4 and N_2O is as follows:

$$f_i(x, t_E) = e^{-\frac{x - t_E}{\tau_i}} \tag{6}$$

where τ_i represents the lifetime of GHG i in the atmosphere (year; CH_4 and N_2O with a lifetime of 12.4 and 121 years, respectively).

For CO_2, the decay function of CO_2 is as follows:

$$f_{CO_2}(x, t_E) = a_0 + \sum_{i=1}^{3} a_i e^{-\frac{x - t_E}{\tau_i}} \tag{7}$$

where parameters of $a_0 = 0.2173$, $a_1 = 0.2240$, $a_2 = 0.2824$, $a_3 = 0.2763$, $\tau_1 = 394.4$, $\tau_2 = 36.54$, $\tau_3 = 4.304$ of IPCC AR5 were used, in addition to the parameters of 16 CO_2 impulse-response functions summarized by Joos *et al.* (2013). Supplementary Table 8 gives details[26].

Referring to Eqs. 4-7, the TRF of the three greenhouse gases of CO_2, CH_4, and N_2O were derived as Eqs. 8-10.

$$TRF_{CO_2}(t) = a_0 {t^2}/{2} + \sum_{i=1}^{3} a_i \left\{ \tau_i t - \tau_i^{\,2} \left(1 - e^{-{t}/{\tau_i}} \right) \right\} \tag{8}$$

$$TRF_{CH_4}(t) = RE \left\{ \tau_{CH_4} t - \tau_{CH_4}^{\,2} \left(1 - e^{-{t}/{\tau_{CH_4}}} \right) \right\} \tag{9}$$

$$TRF_{N_2O}(t) = RE \left\{ \tau_{N_2O} t - \tau_{N_2O}^{\,2} \left(1 - e^{-{t}/{\tau_{N_2O}}} \right) \right\} \tag{10}$$

RESULTS

Comparison of climate performance at the baseline

Figure 2 shows the GWP of fresh lettuce cultivated by traditional sunlight greenhouse and by plant factory. In the baseline of China Southern Power Grid, the 100-year GWP of 1 kg of lettuce produced in the plant factory is over 50 times higher than that of cultivated in the greenhouse. The methane (nitrous oxide) emissions contribute 9(14)% to the GWP of greenhouse and 16(1)% to plant factory [Figure 2A]. The application of nitrogen fertilizers (70%-75%) and polyethylene film (10%-14%) are the two main sources of GWP for greenhouse; while power consumption (43%-99%, Figure 2B) is the largest contributor to the GWP of plant factory. The climate performance of the plant factory varies with power sources. For example, the 100-year GWP of plant factory powered by fossil fuels (13-25 $kgCO_2e$ in P_{1-3}, which represent plant factory that uses coal, oil, and natural gas to generate electricity, respectively) is substantially higher than

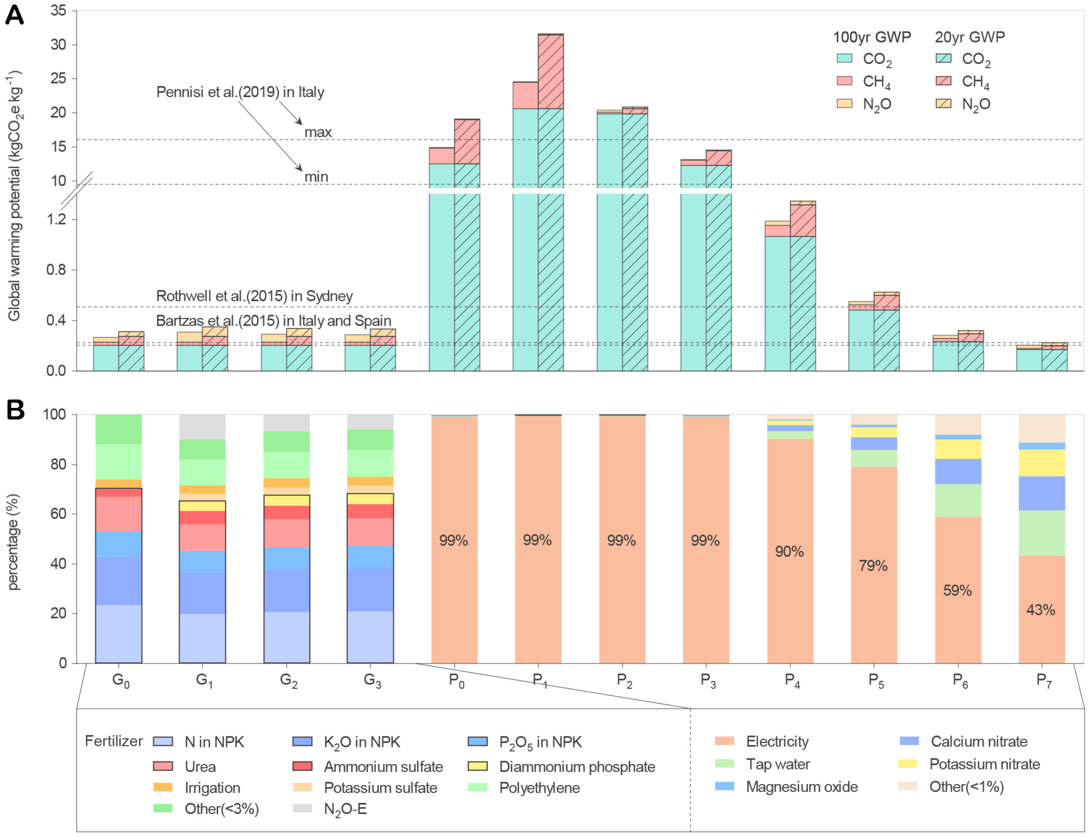

Figure 2. Global warming potential (GWP) of fresh lettuce cultivated in the sunlight greenhouse (G) and plant factory with artificial light (P). (A) The 100(20)-year GWP. Greenhouse: Baseline G_0 excludes the N_2O emission of nitrogen fertilizer uses, and $G_{1\text{-}3}$ consider N_2O with three separately measured emission coefficients[20-22]. Plant factory: P_0 represents baseline power sources from China Southern Power Grid and others from coal (P_1), oil (P_2), natural gas (P_3), solar (P_4), wind (P_5), nuclear (P_6), and hydro (P_7). (B) Material contributions to the 100-year GWP.

that by clean sources (0.2-1.2 $kgCO_2e$ in $P_{4\text{-}7}$, which represent plant factory that uses solar, wind, nuclear, and hydro to generate electricity, respectively). The 20-year GWP exceeds its 100-year counterpart. Notably, if the plant factory were fully powered by nuclear and hydro sources, the GWP would substantially decline down to the values of lettuce produced in the greenhouse (P6 and P7 in Figure 2A).

Sensitivity analysis for LCA models

To identify the key materials input on the climate performance of traditional greenhouses and plant factories, we conducted the sensitivity analysis [Figure 3]. For greenhouse cultivation [Figure 3A], the GWP metric was the most sensitive to the changes in nitrogen fertilizer consumption, e.g., for the 100-year GWP indicator, an increase of 11% and 3% was observed for a 20% increase in the consumption of nitrogen-phosphorus-potassium compound fertilizer and urea, respectively. Polythene trellis film was the second sensitive contributor to the GWP variations, which increased by 3% for a 20% growth in consumption. By contrast, the climate performance of plant factories was most sensitive to electricity consumption [Figure 3B]. A 5% increase in electricity consumption (China's Southern Power Grid as baseline) was associated with an equivalent 5% growth in the 100-year GWP indicator. Notably, variations in the water and nutrient solution inputs had little effect on the climate performance of plant factory cultivations.

Grid decarbonization effect on plant factory's performance

Based on China's Southern Grid, we quantified the GWP of plant factory cultivation by developing the LCA model (See P_0 in Figure 2A). To examine the effect of grid decarbonization on the climate performance of

Figure 3. Sensitivity analysis of life cycle models to identify these critical materials input to the GWP outcomes. (A) and (B) represent greenhouse and plant factory cultivations, respectively.

plant factory cultivation, we clustered all the reviewed 64 China's grid decarbonization pathways into 12 scenarios [Figure 4A].

All scenarios, belonging to the two high and low decarbonization levels, have the potential to decrease the climate burden of plant factories compared with the baseline grid. For example, in the 2025-Low decarbonization scenario (with power source composition: 53% coal, 4% natural gas, 10% solar, 10% wind, 7% nuclear, and 16% hydropower), one kilogram of lettuce produced in a plant factory emits 13.9 $kgCO_2e$ and 17.7 $kgCO_2e$ of greenhouse gases at 100-year and 20-year scales, respectively, which is 7%-8% lower than the baseline emissions (P_0). If the coal-fired power was phased out in the 2050-High decarbonization scenario, the GWP of plant-factory cultivations would decline by one order of magnitude. However, this lower GWP is still five times higher than that of the greenhouse cultivations (G_0 in Figure 2A). Notably, under low and high levels of grid decarbonization, the 20-year GWP of the plant factory is 13%-27% higher than the 100-year counterpart [Figure 4B].

Grid decarbonization decreases the TWP metrics over time, reflecting the rising relative climate performance of the plant factory versus the greenhouse [Figure 4C]. However, the plant factory still fails to show absolute climate advantage, although nitrous oxide emission further offsets the greenhouse's performance ($TWP_{CH4+N2O} < TWP_{CH4}$). This failure is reflected by the TWP range 5-66, much higher than the crossover point at 1. Even when using solar, wind, and nuclear as alternative power sources, the production of lettuce in plant factory still generates a larger climate impact than in traditional greenhouse. Only when fully powered by hydropower did the plant factory perform better than the greenhouse.

Upstream methane and nitrous oxide emissions

Figure 5 shows the contrition of various greenhouse gasses to the total climate burdens of plant factory cultivation. Under the varied grid decarbonization scenarios, carbon dioxide unsurprisingly dominates

Figure 4. The effect of grid decarbonization on the climate performance of the plant factory. (A) Power source mix of China's grid decarbonization scenarios (C-coal, G-natural gas, S-solar, W-wind, N-nuclear, and H-hydro). Heat maps represent 64 decarbonization pathways (rows) clustered into 12 high- and low-scenarios. (B) GWP of plant factory at high- and low-decarbonization levels. The reference is the GWP baseline on China's Southern Power Grid. (C) the corresponding TWP. TWP < 1 means the plant factory is more beneficial to the climate than the greenhouse, and vice versa for TWP > 1, and TWP = 1 means the equivalent climatic performance. The uncertainties were sourced from 17 CO_2 impulse-response models[16]. The left y-axis represents the metrics of TWP_{CH4} and $TWP_{CH4+N2O}$, while the right y-axis represents the inverted U-belts reflecting the deficiency between TWP_{CH4} and $TWP_{CH4+N2O}$.

84%-90% of the life cycle climate burden of lettuce cultivations by plant factory, contrasting with the 9%-15% share of the upstream methane emissions. For most scenarios of grid decarbonization, more than 90% of methane emissions come from the coal combustion of upstream power generations. However, in the 2050-high decarbonization scenario, the share of upstream methane emissions decreases to about 4% of the overall climate burden. This can be attributed to the dramatic phase-out of coal-fired power generation. In addition, grid decarbonization has less impact on nitrous oxide emissions, which share the least amount.

DISCUSSION

Given the short-lived methane emissions from upstream power generations and nitrous oxide emissions from fertilizer uses, we developed the LCA models to quantitatively compare the GWP of lettuce grown by plant factory and greenhouse. TWP metric was developed to dynamically compare the climate advantage of the two vegetation cultivation systems through cumulative radiative forcing of multiple GHGs. For greenhouse, the 100-year GWP of 1 kg lettuce is comparable with previous estimates in Italy and Spain

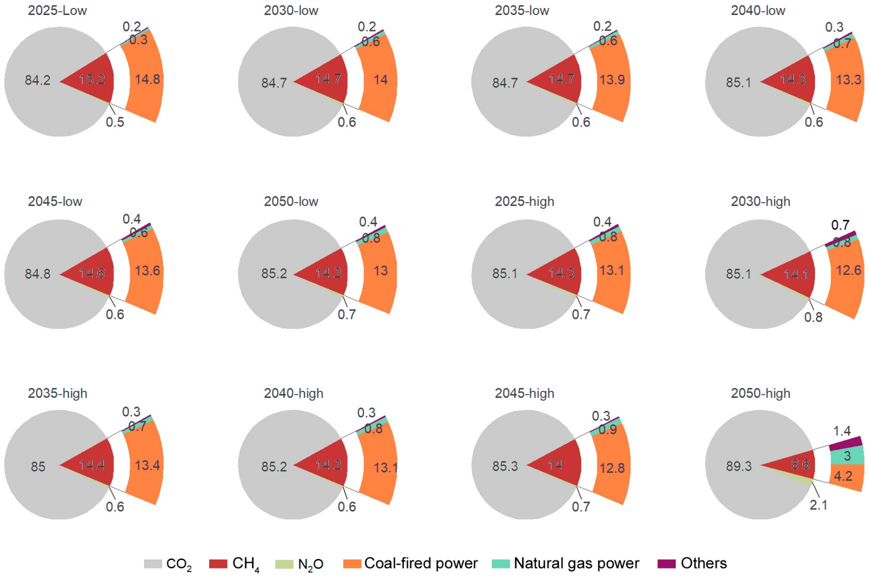

Figure 5. The composition of life cycle climate burdens of the lettuce cultivated in plant factories under multiple scenarios of China's power grid decarbonizations.

(~0.2 kgCO$_2$e t^{-1})[11], but slightly lower than that in Sydney (~0.5 kgCO$_2$e t^{-1})[12]. Nitrous oxide emissions increase the GWP of greenhouse cultivation by 7%-15%, referring to the baseline with no nitrous oxide emissions from fertilizers (See G$_0$ and G$_{1-3}$ in Figure 2A). For plant factory cultivation, the GWP magnitude approaches the upper estimate in Italy (~17 kgCO$_2$e t^{-1})[13].

Our analysis shows that the 20-year GWP exceeds its 100-year counterpart by life cycle analysis [Figure 2A]. This is because of the time-dependent cumulative radiative forcing amplified by short-lived GHGs. Notably, uncertainties from multiple sources were introduced when we developed life cycle models. Thus, we further defined two types of triangle and normal probability distributions to conduct the Monte Carlo simulations. The outcome (shown in Supplementary Figure 2) proves the robustness of GWP deficiency of the two lettuce farming systems of traditional sunlight greenhouse and plant factory under 20-year and 100-year time scales. Additionally, for the TWP metric, the uncertainties were within 5% when considering the 16 CO$_2$ impulse-response functions reviewed by Joos *et al.* (2013)[26]. Therefore, these narrowing variations of uncertainties demonstrated the TWP metrics' robustness.

Admittedly, our study has limitations. Firstly, the power supply in this paper, both fossil and clean energy sources, utilizes a wide-region power grid to maintain the operation of the entire plant factory. We failed to consider the possibility that plant factories move away from the wide-region power grid to local electric energy sources. For example, Cossu *et al.* (2023) showed that the local photovoltaic electricity generation system of solar panels is very flexible to power the plant factory and reduce the reliance on a wide-region power grid[27]; the climate performance of typical local electricity supply has also been analyzed[28]. Moreover, the power consumption varies considerably across different LED lighting systems. However, due to the unavailability of data, this study did not analyze the power parameters of the LED lighting system for other crops such as carrot[29], but used the total power consumption of the whole plant factory. Therefore, it would be helpful to improve the accuracy of our analysis if more detailed data were available. Additionally, the sunlight greenhouse in this study refers to a small-scale agricultural facility with a low degree of mechanization, so energy consumption of agricultural machinery was excluded from the life cycle analysis.

However, the climate performance of greenhouses deserves further investigation if agricultural robots or agricultural machinery were deployed in large-scale intelligent greenhouses.

CONCLUSIONS

Non-CO_2 greenhouse gas emissions on dynamic carbon footprints complicate the comparison of the climate performance of two vegetable production systems: Traditional sunlight greenhouses and plant factories. In this study, we used lettuce production as an example and established the LCA models of sunlight greenhouses and plant factories to quantitively compare their climate advantages under different grid decarbonization scenarios, with conclusions as follows.

First, artificial light plant factories have no climate advantage in lettuce production relative to traditional sunlight greenhouses at the baseline scenario. Second, nitrogen fertilizer and polyethylene film consumption in the traditional greenhouse production system are the main sources of greenhouse gas emissions, whereas electricity consumption is a huge contributor to the climate load of the plant factory. Third, scenario analysis shows that power grid decarbonization with upstream methane control added the climate advantage of plant factories, whose climate performance gradually increased over time relative to the greenhouse. Fourth, although nitrous oxide emissions reduce the climate advantage of the traditional sunlight greenhouse, plant factory cultivation still fails to exhibit better climate performance unless it is fully powered by hydroelectricity. Our analysis contributes to the low-carbon development of vegetable production systems in the context of China's power grid decarbonization.

Follow-up investigations can be conducted to further compare the climate performance of greenhouses and plant factories. Firstly, besides polyethylene film, glass is usually used as coverings for sunlight greenhouses. Glass covering materials have a long lifespan but produce high carbon emissions in glass production, so there is a trade-off when selecting the materials of greenhouse coverings for climate performance analysis. Secondly, plant factories or vertical farming facilities can be developed at significantly varied scales, such as urban areas, communities, or even households. Thus, the power sources also vary accordingly, and the top-down and bottom-up technological pathway is needed for local policymakers to choose global optimum vegetable production technologies to avoid troublesome foci[30]. Thirdly, different crops (e.g., lettuce and strawberry) have different demands on temperature, light, nutrients, *etc.* These varied materials input leads to different carbon emissions, which deserves in-depth discussion under varied decarbonization pathways. Fourthly, for crop transportation distance, urban plant factories generally belong to the category of "zero km", thus emitting fewer GHGs, causing less food loss, and keeping high quality by reducing the transport distance compared with vegetables transported from rural areas, which is an interesting topic for further investigation.

Notably, plant factories, as supplements to vegetable production facilities, can not completely replace sunlight greenhouses in China's context. For example, in remote areas with extremely harsh climate conditions (like frontier sentry), plant factories show the potential to provide a sufficient supply of vegetables. This reduces the challenges of long-distance transportation and preservation tasks. Compared to rural greenhouses, urban plant factories also provide cultural and educational services for metropolitan areas. Additionally, building plant factories becomes possible in densely populated urban areas, which enhances the food security of large cities, such as during pandemics[31]. Therefore, climate performance and sustainable production are not the only criteria for judging the feasibility of plant factories in urban areas. The construction of plant factories is also necessary to improve future urban food security. Thus, comparing the climate performance of urban plant factories and rural traditional sunlight greenhouses is an interesting but challenging topic, except for considering the temporal dimensions of the short-lived and powerful

GHGs. A trade-off analysis deserves to be further conducted to balance urban food security and environmental sustainability.

DECLARATIONS

Authors' contributions

Collected data, developed the LCA model, performed data analysis, and developed the original draft: Cheng Y
Designed this study and developed the original draft: Song G
Contributed to the generation of figures: Liu X
Revised and commented the manuscript: Batlle-Bayer L, Fullana-i-Palmer P
Reviewed and edited the manuscript: Cheng Y, Song G, Liu X, Batlle-Bayer L, Fullana-i-Palmer P

Availability of data and materials

All data were available in the Supplementary Material.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable

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