RESEARCH ARTICLE

The Tsing-Agri Farm Paradigm: Integrating Controlled Environment Agriculture with Industrial Systems for a Low-Carbon Future

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Abstract

Agriculture is both a major contributor to and a victim of climate change, accounting for approximately 22–25% of global greenhouse gas (GHG) emissions and facing heightened risks from extreme weather events. International climate frameworks, including the Paris Agreement, emphasize the urgent need for transformative changes in food systems to achieve net-zero emissions by mid-century. In this context, China has pledged to peak carbon emissions by 2030 and reach carbon neutrality by 2060, with agriculture playing a central role. This paper presents the Tsing-Agri Farm, an advanced controlled environment agriculture (CEA) system developed by Beijing TsingSky Technology Co., Ltd., affiliated with Tsinghua University. Each facility, covering 60,000 m^2, is engineered to operate under extreme climate conditions and meet the annual tomato consumption of 100,000 people. Distinctively, the system integrates with adjacent industrial infrastructure to recover waste heat and CO_2, thereby reducing operational costs while enhancing carbon sequestration. The carbon mitigation effect of every 100 acres of such farms is comparable to that of 16,000 acres of photovoltaic installations, highlighting its significant climate benefits. By examining the technical design, carbon reduction potential, and operational resilience of the Tsing-Agri Farm, this study contributes to the discourse on climate-smart agriculture and demonstrates a scalable model for sustainable, low-carbon food production under future climate uncertainties.

Keywords: extreme weather, food security, industrial-agricultural integration, controlled-environment agriculture, agricultural carbon sequestration.

1 Introduction

Agriculture stands at the nexus of contributing to and being adversely affected by climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), agriculture—including land-use change, fertilizer production, livestock, and energy use—accounts for approximately 22–25% of global

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greenhouse gas (GHG) emissions [1]. These emissions are projected to increase by 20–30% by 2050, driven by growing food demand, dietary transitions, and population expansion (FAO, 2021) [2]. At the same time, agricultural systems are increasingly vulnerable to climate-induced stresses, including prolonged droughts, temperature variability, and intensified natural disasters [3]. This dual role highlights the urgent need for transformative measures within the agri-food sector to ensure global food security while mitigating environmental impacts.

In recognition of these challenges, international climate frameworks have underscored the critical importance of agricultural transformation. The Paris Agreement (2015) commits nations to limiting global warming to well below 2 °C above pre-industrial levels [4], with aspirations of capping it at 1.5 °C, thereby necessitating net-zero GHG emissions by around 2050. The IPCC Special Report on 1.5 °C further emphasizes that achieving these targets requires "rapid and far-reaching transitions" in land use, energy, industry, and agriculture [5]. Many regions have already incorporated agriculture into decarbonization pathways, with examples including the European Union's Green Deal [6], France's "4 per 1000" soil carbon initiative, Germany's nitrogen surplus regulations, and the U.S. Growing Climate Solutions Act [7]. Meanwhile, developing countries such as India, Brazil, and Southeast Asian nations have focused on soil rehabilitation, water-efficient irrigation, and smallholder-oriented climate adaptation technologies [8].

Within this global context, China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, with agricultural transformation as a critical component [9]. Despite possessing only 7% of the world's arable land, China is tasked with feeding 22% of the global population [10]. In 2018, agricultural activities accounted for 861 million tons of CO_2-equivalent emissions, prompting national strategies such as the Sustainable Agricultural Development Plan (2015–2030) and the Green Agricultural Development Guidelines (2018–2030) [11]. These policies aim to reduce methane and nitrous oxide emissions, enhance soil health, and promote climate-smart practices across croplands and livestock systems.

It is against this backdrop that Beijing TsingSky Technology Co., Ltd. ("TsingSky"), affiliated with Tsinghua University, has emerged as a pioneering agricultural technology enterprise. Officially registered in 2014 under the leadership of Xiaoqing Wang, a graduate of Tsinghua University's PBC School of Finance, TsingSky was founded to address critical challenges in China's agricultural future—namely, who will cultivate the land, how to standardize vegetable production, mitigate hidden hunger, and ensure food security. Drawing on a multidisciplinary team of experts from non-agricultural fields, the company has devoted over a decade to the development of the Tsing-Agri Farm, an advanced controlled environment agriculture (CEA) system tailored for large-scale, high-efficiency vegetable production.

The Tsing-Agri Farm is specifically engineered to withstand extreme climate conditions, including temperature ranges from -30 °C to 45 °C, heavy rainfall (140 mm/day), typhoons up to Category 18, and earthquakes up to magnitude 8. Each facility spans 60,000 m^2—sufficient to meet the annual tomato consumption needs of 100,000 people—and integrates with industrial infrastructure such as power plants, textile dyeing plants, and waste incineration facilities. By recovering waste heat and CO_2 emissions from adjacent industries, the system reduces operational costs and enhances carbon sequestration capacity. Notably, the carbon mitigation potential of every 100 acres of Tsing-Agri Farms is equivalent to that of 16,000 acres of photovoltaic installations, underscoring its environmental significance.

Tomatoes, as a strategic focus crop, were selected for their capacity to grow continuously and be harvested year-round under moderate temperatures (10–30 °C) [12]. This biological advantage makes them an ideal entry point for industrialized agricultural solutions addressing global modernization challenges [13]. Building on this foundation, the Tsing-Agri Farm has been recognized as a model for future farms, digital farms, common prosperity farms, and low-carbon farms. This paper introduces the Tsing-Agri Farm paradigm as a practical and scalable solution for integrating industrial and agricultural systems. Through an analysis of its technical pathways, carbon mitigation potential, and operational resilience [14], the study contributes to the discourse on climate-smart agriculture and demonstrates a replicable model for sustainable, low-carbon food production under future climate uncertainties.

2 Goal Setting for the Tsing-agri Farm

Establishing clear and well-defined objectives is essential for structuring research and ensuring efficient technological implementation. The TsingSky team applied industrial project planning methodologies to agricultural development, setting precise goals to guide innovation. Key objectives include:

- **Environmental Adaptability:** Maintain continuous agricultural production within temperature ranges of -35 °C – 45 °C and relative humidity levels of 30 % – 80 % in various regions of China [15].
- **Quality Standards:** Ensure compliance with strict safety and nutritional standards regarding pesticides, hormones, heavy metals, nitrites, bacterial counts, and overall nutritional value, alongside high standards for appearance, color, flavor, sugar-acid ratio, and cooking performance.
- **Yield Assessment:** Maximize annual effective fruit yield per unit area to enhance production efficiency.
- **Cost Control:** Incorporate both traditional economic costs (including fixed asset depreciation and variable expenses such as materials, labor, and maintenance) and ecological costs (such as water, energy, and fertilizer consumption per kilogram of produce).
- **Sustainability Metrics:** Evaluate the project's impact through indicators such as carbon reduction per kilogram of produce, water conservation, environmental friendliness, labor welfare, consumer health benefits, and the mitigation of hidden hunger.

Figure 1. The production scenario of the Tsing-Agri Farm.

These objectives collectively define the foundation of the Tsing-Agri Farm's production system, as depicted in Figure 1.

3 Industrial Integration and Practical Applications

The research and development process at TsingSky revealed that energy costs are a major constraint on the industrialization of agriculture. A comparative analysis between traditional open-field farming and the Tsing-Agri Farm highlights the significant performance and sustainability advantages of the latter, as shown in Figure 2. In terms of productivity, the Tsing-Agri Farm yields between 50 to 60 kg/m^2/year, representing a 6 to 8-fold increase over traditional farming, which typically produces only 7.5 kg/m^2/year. Despite the dramatic yield difference, the Tsing-Agri Farm model uses only 8 liters of water per kilogram of produce, compared to 320 liters in traditional farming systems. This represents a 40-fold improvement in water use efficiency, highlighting the system's capacity for high productivity with minimal resource consumption. Furthermore, fertilizer input per unit output is dramatically reduced in the Tsing-Agri Farm. Notably, the Tsing-Agri Farm operates entirely without pesticides, eliminating chemical residues and associated environmental risks, while also adhering to international food safety standards (SGS certification), unlike the uncertified traditional counterpart. From a supply chain perspective, the Tsing-Agri Farm employs low-emission transport solutions, minimizing fossil fuel reliance. Most strikingly, the full lifecycle product loss is reduced to less than 5 %, compared to approximately 45 % in traditional systems, due to intelligent post-harvest handling and localized distribution. Collectively, these metrics underscore the Tsing-Agri Farm's superior resource efficiency, environmental compatibility, and scalability as a low-carbon agricultural model.

Traditional agricultural production relies heavily on natural gas for heating, yet it also requires cooling to regulate greenhouse temperatures, making energy costs a significant bottleneck. To address this, the team developed strategies to reduce the energy load of glass greenhouses by enhancing insulation materials, improving structural sealing, optimizing ventilation control (such as window angles, insect screens, and airtight closures), and refining planting methods. These measures reduced thermal and cooling loads from the conventional 20 W/m^2/°C to an optimal 4 W/m^2/°C.

Furthermore, TsingSky introduced a flexible energy management solution that utilizes waste heat from

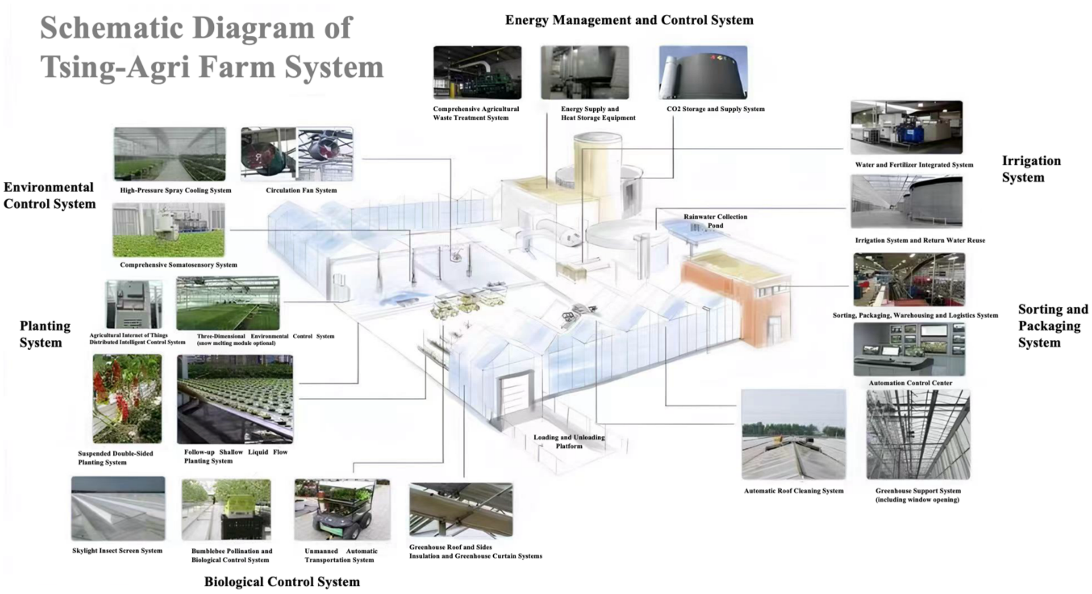

Figure 2. Schematic diagram of Tsing-Agri farm system.

coal-fired power plants. By leveraging different forms of waste heat—such as 115°C end-stage steam, 35°C cooling tower water, 55°C recycled heating water, and flue gas emissions—the team minimized energy costs while simultaneously repurposing CO_2 emissions as plant nutrients to enhance tomato photosynthesis.

This model has been successfully implemented in various industrial settings, including:

- **The Tsing-Agri Farm at Mengdian Power Plant, Henan Province** (utilizing power plant waste heat and CO_2 recycling). Based on the waste heat and CO_2 generated by the Mengdian Thermal Power Plant, and using the vegetable factory developed and designed by TsingSky as a carrier, a carbon-rich vegetable factory that integrates industry and agriculture is formed. The waste heat serves as the heat source of the vegetable factory, and the CO_2 becomes a gas fertilizer for vegetable cultivation. Carbon is fixed through vegetable photosynthesis, while saving 95% of water, 45% of fertilizer, and 99% of manual labor. It can produce vegetables year-round, producing 30 times the international standard of safe vegetables compared to field production, and can also fix and save up to 20,000 tons of carbon, as illustrated in Figure 3.

Figure 3. Schematic Layout of the Tsing-Agri Farm Integrated with Mengdian Power Plant.

- **The Tsing-Agri Farm near a reservoir in Huangchuan, Henan Province** that utilizes water-based temperature regulation, suitable for hot climates (Industry + Agriculture + Science and Technology + Business Integration). This system leverages the reservoir's thermal stability to moderate greenhouse conditions, enabling efficient vegetable cultivation under high-temperature environments and ensuring sustainable year-round production, as shown in Figure 4.

Figure 4. Schematic of the Tsing-Agri Farm near a Reservoir in Huangchuan.

- **The Tsing-Agri Farm in an urban park in**

Gucheng, Hebei Province (utilizing waste heat from municipal heating systems). This model demonstrates how agricultural production can be embedded within urban ecosystems, recycling surplus thermal energy from district heating networks to support controlled environment agriculture while contributing to food security and low-carbon urban development, as illustrated in Figure 5.

Figure 5. Schematic of the Tsing-Agri Farm in an Urban Park in Gucheng.

3.1 Case Study: Tsing-Agri Farm at Mengdian Power Plant, Henan Province

The integration of the Tsing-Agri Farm with the Henan Mengdian Thermal Power Plant exemplifies the efficient utilization of industrial byproducts for sustainable agriculture. By repurposing waste heat and CO_2 emissions, the project reduces energy costs, enhances agricultural productivity, and promotes carbon sequestration, as illustrated in Figure 6.

The project aims to optimize resource use by utilizing waste heat from power generation for greenhouse heating, significantly lowering energy consumption. Additionally, it captures and applies CO_2 emissions as a carbon fertilizer, increasing crop yields by enhancing photosynthesis efficiency. Through this approach, it establishes a replicable low-carbon agricultural model that can be adopted in other industrial zones.

To achieve these objectives, the project integrates multiple engineering solutions. Waste heat is recovered from 115°C flue gas steam, 35°C cooling tower waste heat, and 55°C heating return water to maintain stable greenhouse temperatures. CO_2 fertilization is implemented by purifying and delivering emissions to the greenhouse, raising CO_2 concentration to 1000 – 1200 ppm and accelerating plant growth. The greenhouse is also designed to withstand Henan's climate variations, ensuring continuous year-round production.

Since its implementation, the project has yielded significant results. Energy costs have been reduced by 40% through efficient waste heat utilization. Each hectare of greenhouse sequesters approximately 500 tons of CO_2 annually, equivalent to the carbon capture of thousands of trees. Agricultural productivity has increased dramatically, with tomato yields per unit area reaching 50 times that of open-field cultivation while maintaining superior quality and extended shelf life. Moreover, the model offers strong scalability, providing a viable low-carbon agricultural solution for industries such as power, cement, and chemicals to facilitate carbon reduction and resource recycling.

By demonstrating the synergy between agriculture and industry, this model provides a scalable solution for low-carbon food production. Its success paves the way for further applications in urban heating, cement, and steel industries, contributing to global sustainability goals.

4 Agricultural Carbon Sequestration as A Future Revenue Model

Agriculture has traditionally relied on government subsidies to maintain stable food prices and prevent ripple effects on industrial and service sector costs. However, in the context of sustainable development, agricultural carbon sequestration is emerging as a vital source of supplementary revenue. Agricultural carbon sequestration primarily consists of two key components:

- Carbon Fixation in Agriculture: Through photosynthesis, plants absorb CO_2, and controlled greenhouse environments enable higher CO_2 concentrations (from 300 ppm to 1200 ppm), increasing fixation efficiency. Research indicates that forests typically sequester 0.582 tons of carbon per mu per year, whereas vegetable factories can achieve up to 40 tons per mu per year.
- Carbon Reduction in Agriculture: Sustainable practices such as water recycling (reducing tomato water consumption from 260 L/kg to 8 L/kg), efficient fertilizer use (nearly 100% reuse), recyclable packaging, and localized distribution significantly lower carbon emissions.

Furthermore, integrating industrial waste heat and CO_2 utilization directly into agricultural processes

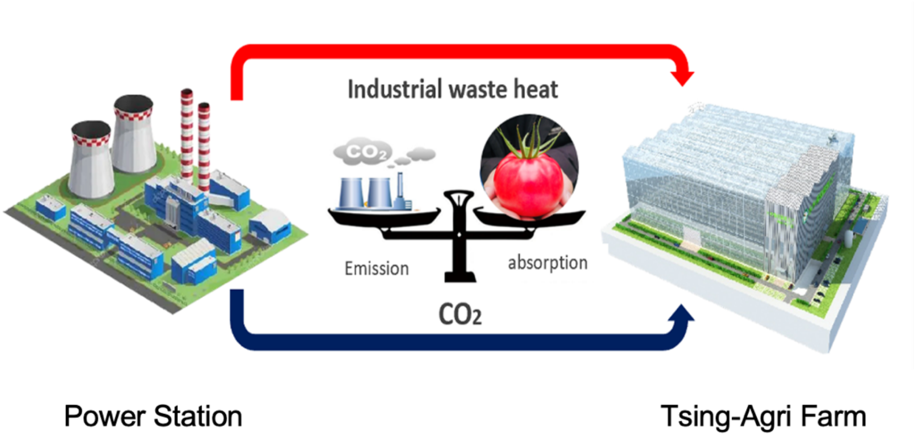

Figure 6. Integration of the Tsing-Agri Farm with the Henan Mengdian Thermal Power Plant through Waste Heat and CO_2 Recycling.

presents an effective strategy for reducing industrial emissions. For example, thermal power plants can enhance energy efficiency by repurposing flue gas heat for greenhouse production, creating a closed-loop carbon sequestration system.

5 Barriers and Strategies for Replication in Developing Countries

Although the industrial–agricultural integration model exemplified by the Tsing-Agri Farm demonstrates notable advantages in improving agricultural productivity, reducing carbon emissions, and supporting climate-smart agriculture, replicating this model in developing countries faces several practical challenges.

First, disparities in infrastructure and energy structure pose significant barriers to replication. The Tsing-Agri model relies on stable sources of industrial waste heat and CO_2 emissions from facilities such as coal-fired power plants, chemical factories, and waste incineration plants. However, in many developing countries, industrial development is either limited or geographically dispersed, making it difficult to achieve physical proximity and operational synergy between industrial and agricultural systems. In addition, many regions are still dominated by traditional agriculture with limited integration with heavy industry.

Second, the high initial capital investment and lack of financing channels are major obstacles. The model requires investment in high-strength greenhouse structures, precision environmental control systems, and digital monitoring platforms. While the long-term operational efficiency and environmental benefits are significant, governments and agricultural enterprises in developing countries often lack sufficient financial capacity to launch such capital-intensive projects.

Third, a shortage of local technical expertise and skilled operators can hinder implementation. The system depends on intelligent environmental regulation, CO_2 concentration control, and crop prediction algorithms, which require multidisciplinary knowledge in engineering, agronomy, and digital systems. In regions with a low level of agricultural modernization, the absence of a qualified workforce increases the risk of operational failure.

Fourth, the policy and institutional environment in many developing countries is not yet conducive to integrated low-carbon agriculture. Effective deployment of this model requires policy alignment across multiple sectors—agriculture, energy, and environmental protection. However, many countries lack supporting mechanisms such as carbon trading markets, green subsidies, or industrial-agriculture coordination frameworks. To address these challenges, the following strategies are proposed:

Modular and adaptable system design: Develop lower-cost, modular versions of the system that can be customized for local conditions, including alternative heat sources such as solar thermal or geothermal energy.

Pilot demonstration and technology transfer:

Promote international cooperation to establish pilot projects led by experienced countries or multilateral organizations, providing proof-of-concept and enabling local adaptation through joint ventures and training programs.

Leverage climate finance and multilateral funding: Mobilize resources from mechanisms such as the Green Climate Fund and the Clean Development Mechanism to provide seed funding for project development and encourage private sector investment in sustainable agriculture.

Invest in local capacity building and digital platforms: Establish localized training systems and remote technical support platforms to empower local operators and reduce dependence on high-level expertise. AI-assisted control systems can help automate complex decision-making.

Strengthen national-level policy frameworks: Encourage developing countries to integrate industrial–agricultural models into national green development strategies, and introduce incentives such as carbon credit schemes, green investment channels, and land-use planning support.

6 Conclusion

As of early 2025, the Tsing-Agri Farm has achieved a fiftyfold increase in production efficiency compared to traditional open-field farming, while maintaining a localized, closed-loop farm-to-table model that minimizes lifecycle losses and logistical emissions. Through the integration of industrial waste heat and CO_2 emissions, the system enables significant carbon reductions, with the carbon sequestration impact of every 100 acres of greenhouse production equivalent to that of 16,000 acres of photovoltaic installations. Additionally, the project has successfully implemented carbon measurement, reporting, and verification (MRV) systems, contributing to the development of standardized methodologies for agricultural carbon accounting and credit generation.

The model also demonstrates superior performance in resource use: maintaining the same water input per unit as conventional farming while achieving much higher output, drastically reducing fertilizer use, and eliminating pesticide applications. These characteristics support both environmental sustainability and food safety, as evidenced by international certifications such as SGS.

In conclusion, the Tsing-Agri Farm paradigm represents a viable and scalable innovation for climate-smart agriculture, offering compelling benefits in productivity, environmental footprint, and economic potential. However, its replication in developing countries must be approached with consideration of local infrastructural constraints, financial capacity, and technical readiness. A phased deployment strategy—grounded in technological modularity, climate finance mechanisms, and capacity-building programs—can facilitate successful localization and long-term adoption.

Looking ahead, the Tsing-Agri team is working to further refine the system's digital infrastructure, including AI-driven crop forecasting, autonomous environmental control, and integrated carbon monitoring. These advancements will not only enhance operational precision and scalability but also improve the accessibility of the technology for diverse agro-climatic zones. As a next step, international demonstration projects and public–private partnerships will be critical in extending the benefits of this model to address global food security challenges and promote low-carbon agricultural transitions in both emerging and developed economies.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Yiyi Wang is an employee of Shanghai Institute of Finance for Technology Entrepreneurship, Shanghai, China. Xiaoqing Wang is an employee of Beijing TsingSky Technology Co.Ltd, Beijing, China.

Ethical Approval and Consent to Participate

Not applicable.

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