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Techno-Economic Evaluation of Soilless Greenhouse Clusters: Part 1: The Geothermal GOAZ (Greenhouse Organized Agricultural Zone) Model in Türkiye

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INFORMATION

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Abstract
In recent years, global crises, geopolitical conflicts, and climate change have brought food security to the forefront of the macroeconomic agenda and necessitated a transition to technology-intensive agricultural systems. This study presents a comprehensive techno-economic evaluation of soilless greenhouse clusters, drawing on a nationwide empirical case study of the Geothermal GOAZ (Greenhouse Organized Agricultural Zone) model in Turkiye. The analysis examines in detail the cost-reducing effect of centralized geothermal heating, its capacity to make agricultural production independent of fossil-fuel price shocks, and the stability of market supply dynamics in the context of the Cobweb Theorem. Additionally, this framework evaluates the integration of industrial symbiosis, Public-Private Partnership (PPP) governance, and the structural alignment between the EU Green Deal and the Carbon Border Adjustment Mechanism (CBAM). Statistical regression models empirically demonstrate the project's high financial predictability and confirm that spatial clustering meticulously optimizes capital expenditures (CAPEX) through economies of scale. The study also highlights the model's strong Environmental, Social, and Governance (ESG) performance, particularly in generating zero-emission carbon credits and promoting rural employment that supports gender equality. In conclusion, the Geothermal GOAZ model offers a mathematically validated, financially reliable, and scalable framework for sustainable agriculture. Furthermore, by integrating shallow geothermal heat pump technologies into the model, this central clustering model becomes globally applicable across all geographic and climatic conditions, including regions without hydrothermal resources.

Keywords
Geothermal greenhouse, Geothermal GOAZ (Greenhouse Organized Agricultural Zone), Agro-industrial clustering, Public-Private Partnership (PPP), ESG metrics, Industrial symbiosis

1. Introduction

Food security remains a vital global challenge in the 21st century. Extreme weather events driven by the climate crisis, such as droughts, frosts, and storms, along with water resource depletion and shrinking agricultural lands, present serious risks to the sustainability of traditional open-field farming and the stability of food prices (IPCC, 2022).

In this context, controlled agricultural practices such as protected cultivation and greenhouse farming are seen as key strategies for reducing reliance on weather variability and ensuring a consistent food supply year-round (Benke and Tomkins, 2017; Gomez et al., 2019; Cowan et al., 2022). Financial viability in modern greenhouse investments depends on balancing initial costs with operational expenses.

However, a major obstacle in modern greenhouse farming is heating costs, which can make up 50-85% of total production expenses. Heating fueled by fossil fuels such as natural gas not only raises costs but also increases the carbon footprint (Rosas-Casals et al., 2022; Zhu et al., 2022; Carotti et al., 2023; Shortall et al., 2024; Apostolopoulos et al., 2026).

Turkiye is making intensive efforts to fundamentally transform greenhouse heating, which is driven by fossil fuels such as natural gas and contributes to both cost inflation and a carbon footprint, by leveraging its rich geothermal resources. It has also been working diligently in recent years to ensure the security of crop supplies.

It is becoming increasingly clear that these efforts will make a significant contribution to expanding the scope and volume of agricultural production and bringing price fluctuations in agricultural products under control. In Turkiye, in agricultural production (TTB, 2020-2025);

- Introducing newly developed high-yielding and superior varieties into production,
- Increasing production and productivity while ensuring sustainability,
- Disseminating new methods, technologies, and cultural practices to producers,
- Enhancing agricultural mechanization,
- Bringing fallow lands and non-arable areas into production,
- Directing crop production to facilitate integration with the agricultural and industrial sectors,
- Preventing pollution resulting from agricultural activities,
- Determining and monitoring the appropriateness of inputs and production technologies used in crop production,
- Registering, monitoring, and developing protected cultivation,
- Efforts to develop infrastructure in regions suitable for greenhouse farming are being carried out intensively on a project-by-project basis in Turkiye.

Turkiye is one of the countries with the world's richest geothermal resources. Although these resources have traditionally been used for thermal tourism, residential heating, and electricity generation, their use in agriculture has become a strategic national policy in recent years. Currently, about half of the global installed capacity of geothermal-heated greenhouses (1,400 MWt, 7,000 decares) is in Turkiye alone (Çelmen et al., 2025). The "Greenhouse Organized Agricultural Zones (Greenhouse OAZs or GOAZs)" vision, developed under the leadership of the Ministry of Agriculture, aims to unify scattered greenhouse investments into a coordinated clustering system and position Turkiye at the center of the global food supply chain (Fig. 1) (TTB, 2020-2025)

In Turkiye, GOAZ projects have boosted production capacity for plant cultivation. With investments in geothermal greenhouses and nearly a billion dollars in government credit support, a new era in agriculture has begun, with the government, local authorities, civil society organizations, and private-sector companies acting as project partners. This collaboration is driving strategic growth in the country's agricultural sector. According to production projections, plant output targets are 400,000 tons in 2026, 850,000 tons in 2027, and 1,100,000 tons in 2028. In the GOAZs that became operational, crop production reached 10,000 tons in 2023, 22,000 tons in 2024, and 60,000 tons in 2025 (TTB, 2020-2025).

The strategic importance of GOAZs in Turkish agriculture is clearly increasing. There are 24 GOAZ projects in 20 provinces across Turkiye. Among these, 15 are Geothermal GOAZ projects (Fig. 2). Infrastructure for some projects has been finished, and they have opened to investors, aiding both crop production and job creation.

GOAZs are regions where industrial facilities engaged in plant production are grouped by specialized fields of goods and services, enabling control over every stage of production, maximizing yield and quality, promoting low-cost production, and creating employment by supporting development (TTB, 2020-2025). GOAZs are strategically important for energy efficiency and sustainable production.

Despite growing global interest in geothermal greenhouse applications, a critical gap remains in the literature regarding quantitative threshold values and the economic superiority of large-scale clustering models. To address this gap, the primary research questions of this study are:

- What specific engineering-economic advantages do Geothermal GOAZs provide over decentralized, individual greenhouse systems?
- What are the quantitative thresholds that determine the economic superiority of these clustered geothermal systems?
- What is the measurable contribution of geothermal integration to macroeconomic and agricultural sustainability?

Consequently, the central hypothesis of this study is that spatial and functional clustering in Geothermal GOAZs significantly reduces per-decare infrastructure costs and stabilizes production capacity through economies of scale, thereby generating a statistically significant and measurable macroeconomic superiority compared to fragmented, individual greenhouse investments.

As indicated by "Part 1" in the title, this manuscript focuses specifically on the national integration, spatial clustering, and engineering economics of this model in Turkiye. A comprehensive global benchmarking of the system against international practices (e.g., the Netherlands, Iceland, and China) is presented in "Part 2" of this study.

2. Greenhouse OAZs

2.1. Agricultural Supply Chains and New Approaches in the Context of Global Turbulence

Devastating crises experienced worldwide in recent years, such as the COVID-19 pandemic, combined with geopolitical conflicts, demographic shifts, and nationalist policies adopted by governments trying to protect their own food sources, have brought food supply security to the forefront of the global agenda on an unprecedented scale (Bas, 2025; Apostolopoulos et al., 2026). While producers' main concerns in traditional agricultural models usually revolve around fluctuating input costs, today's modern agricultural approach must directly address the devastating impacts of the climate crisis. Unexpected frost events, severe storms, hailstorms, and increasingly prolonged droughts are severely disrupting soil fertility, water reserves, and ultimately the market's supply-demand balance. These weather and environmental disruptions are causing food inflation, making it harder for consumers to access high-quality, affordable food (Fig. 3) (Guiné, 2024; Karagöl, 2025).

Fig. 1. General view of a Geothermal GOAZ project

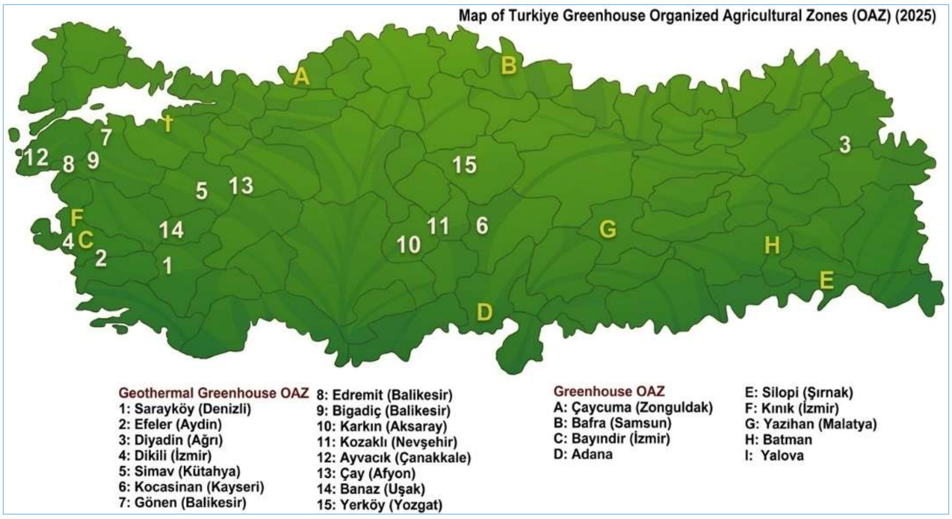

Fig. 2. Geothermal GOAZs and GOAZs are currently in operation or in the process of becoming operational in Turkiye (24 in total)

Considering current ecological risks, greenhouse agriculture serves as a protective barrier against climate fluctuations, particularly for growing fresh fruits and vegetables, and has become a strategic necessity (Dsouza et al., 2023; Bhattarai et al., 2025). Analysis of changes in consumer behavior indicates a rapidly rising demand for trustworthy products free of pesticide residues and sourced through traceable supply chains (Zheng et al., 2022; Filimonau et al., 2024). In this context, it is clear that GOAZs, which enable all processes from production to packaging to be carried out under controlled and traceable conditions, have quickly established themselves in the sector as the most logical and integrated solution for addressing current and future agricultural crises.

2.2. An Application of Clustering Theory to the Agricultural Sector: GOAZ Model

To achieve a sustainable competitive advantage in the agricultural sector, simply increasing the quantity of production factors is not enough. It also requires optimizing their spatial and structural organization (Ye et al., 2023; Li et al., 2025; Du et al., 2026). In this context, the GOAZ model signifies a shift from conventional, fragmented agricultural production to an ecosystem based on industrial symbiosis and clustering (Fig. 4).

Symbiosis is a relationship between different species within an ecological system in which both parties benefits. The core idea of symbiosis is that the advantages two species gain when together surpass those they would each get alone. The concept of industrial symbiosis originated as an approach to building partnerships among industrial companies that typically operate separately, sharing resources for mutual benefit. This approach seeks to mimic the symbiotic (mutually beneficial) relationships found in natural ecosystems within industrial systems. These shared resources can include human resources, logistics, raw materials, waste, and waste heat. Simply put, industrial symbiosis is the process by which one company's byproducts, waste, or unused materials become raw materials for another company. Implementing industrial symbiosis offers social, environmental, and economic advantages across many areas, including more sustainable material use, creating a circular economy, resource efficiency, and new business opportunities. Industrial symbiosis also provides significant chances for the agricultural sector to enhance environmental performance and achieve economic gains (Hamam et al., 2023; Laili et al., 2024; Ulusoy et al., 2024).

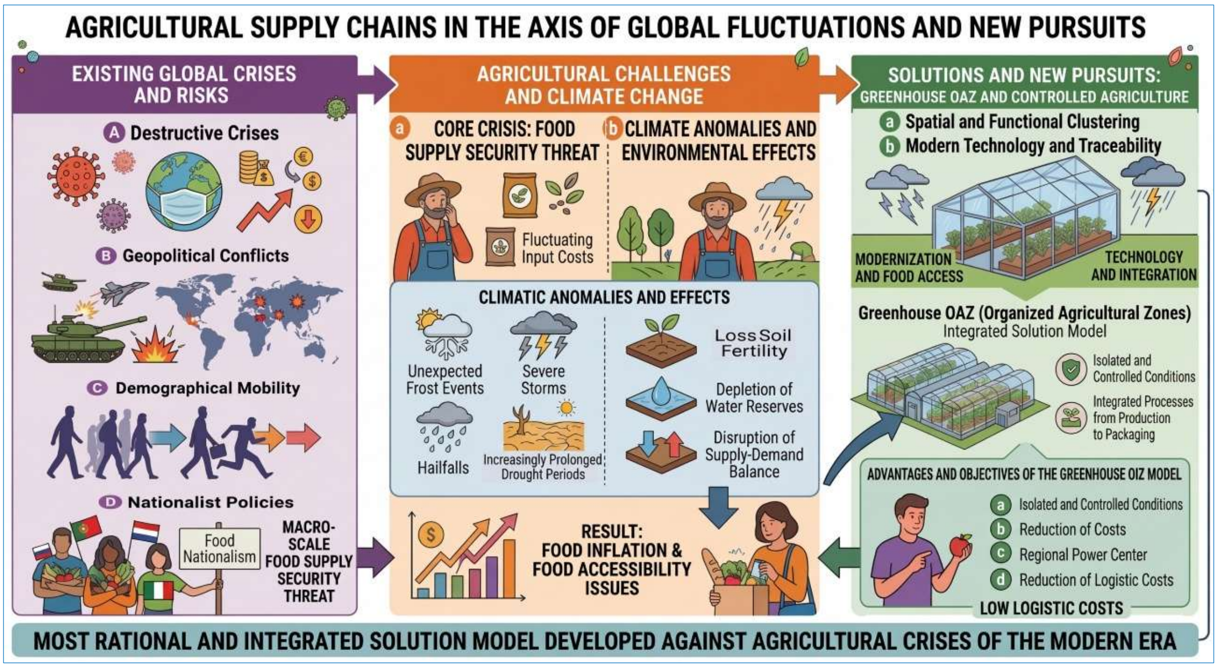

Fig. 3. Agricultural supply chains in the face of global fluctuations and new approaches

GOAZs act as the agricultural sector's counterpart to the industrial symbiosis approach described in the United Nations Development Program (IKA and UNDP, 2022; MEUCC, 2024; Dikili Geothermal GOAZ, 2025). The "clustering" approach, introduced into the literature by Porter (1990), was initially developed for industrial manufacturing sectors but has since become a key analytical tool in the agricultural economy. According to Porter's "Diamond Model," clustering refers to the synergy that results from the concentration of interconnected businesses, specialized suppliers, service providers, and relevant institutions (such as universities, standard-setting agencies, and sectoral associations) within a specific geographic area. Applying this model to agriculture has led to the development of the concept of "Agro-Industrial Clustering". Also, in the agricultural sector, this model corresponds to GOAZs (Fig. 4).

The fragmentation of agricultural land in Turkiye through inheritance, coupled with farm sizes remaining below the thresholds for efficient production (Bozoğlu and Gündoğdu, 2024) and capital shortages faced by small-scale agricultural businesses, weakens producers' competitiveness and slows their adoption of modern production technologies. These include access to modern greenhouse systems that require substantial initial investment, such as soilless farming infrastructure, fully automated climate control systems, and advanced irrigation and fertilization units (Semerci, 2021; Özel and Esmer, 2024). GOAZs create economies of scale by sharing the costs of shared infrastructure (roads, water, electricity, geothermal distribution networks, reinjection wells, etc.) among investors. This lowers barriers for small and medium-sized entrepreneurs who, under normal circumstances, would be unable to establish modern, technologically advanced greenhouses due to high initial investment costs.

In these regions, it is not just greenhouses producing final agricultural products that are clustered together. At the same time, seedling producers, suppliers of biological control agents, packaging factories, cold storage facilities, logistics companies, agricultural R&D centers, and other entities form an integrated chain. In terms of infrastructure, GOAZs are equipped with advanced drinking- and irrigation-water networks, rainwater harvesting systems, telecommunications infrastructure, and modern heating centers. The infrastructure established in these regions, including wastewater treatment, rainwater harvesting, and biomass facilities, serves a fully circular economy model (an integrated ecosystem). For example, plant waste from greenhouses can be converted into energy at biogas facilities, or raw materials needed by packaging plants can be sourced directly from greenhouse outputs. This spatial concentration accelerates the dissemination of information, minimizes transaction costs, and reduces the product's carbon footprint to near zero (Fig. 4).

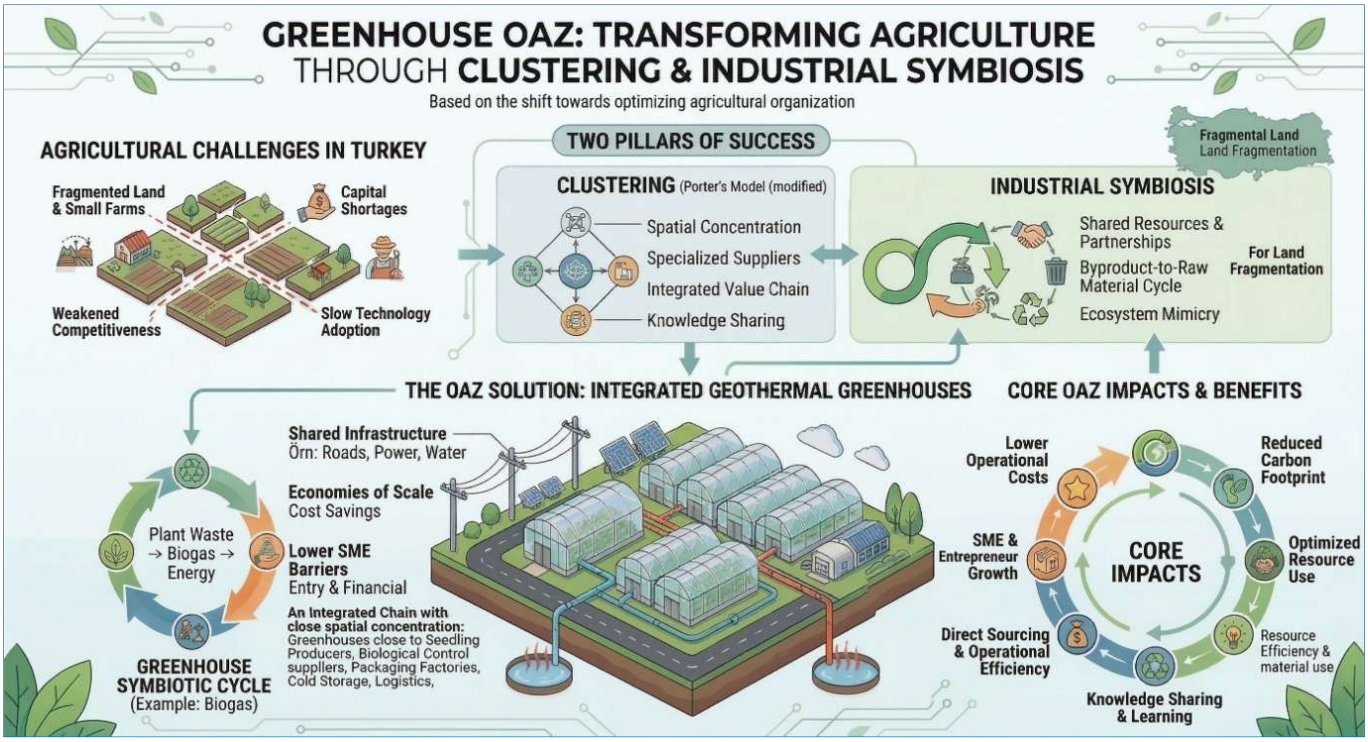

Fig. 4. Geothermal GOAZs as a reflection of Porter (1990) "clustering" theory in the agricultural sector

2.3. GOAZ Philosophy as the Hub of Rural Transformation

The core philosophy of GOAZs is to promote the cultivation of crops such as vegetables, fruits, aromatic plants, and cut flowers by primarily harnessing the regional geothermal potential, thereby increasing both employment and export capacity. The fully automated, technologically advanced, soilless greenhouses being established aim not only to serve the domestic market but also to provide direct access to international markets. During the development process, investors are free to produce according to their chosen models while gaining access to regional, strategic, or large-scale investment incentives and R&D support.

GOAZs are far more than just plant production sites; they are complex structures where cultivation, sorting, packaging, logistics, and marketing operations are integrated into a single ecosystem. These organized structures not only mitigate the effects of the climate crisis but also revitalize local economies, directly boosting social welfare indicators. Designed around the principles of spatial and functional clustering, these zones bring together dispersed producers to create a regional hub. Businesses in high-value sectors, such as traditional greenhouse farming and the cultivation of medicinal, aromatic, and ornamental plants, work together under a shared vision to maximize hygiene standards. Major goals include relocating agricultural activities trapped within urban areas to more suitable sites, standardizing and documenting farming operations, and lowering production costs through clustering.

Additionally, the "Urban Agriculture" concept aims to efficiently meet the daily demand for fresh food in major cities. It reduces logistics costs and reclaims land once considered unsuitable for farming for productive use (TTB, 2020-2025). The main difference between a Geothermal GOAZ and a typical agricultural land allocation is that the former is a planned agro-industrial complex. A typical Geothermal GOAZ layout combines modern greenhouse production areas, industrial facilities for processing, packaging, and storage, renewable energy zones (geothermal, solar, wind, biomass), and administrative and social infrastructure (Figs. 5 and 6).

2.4. Social Impact and Gender-Inclusive Rural Development (ESG Integration)

Aligning directly with the United Nations Sustainable Development Goals (SDGs), the GOAZ model delivers profound Social (S) impact within the corporate ESG framework. Beyond standard macroeconomic indicators, the model systematically restructures regional labor dynamics. With an employment capacity averaging 1.5 persons per decare, the most compelling metric for impact investors is the gender-inclusive workforce: 70-80% of the employees are women. This structural inclusion directly drives women's economic empowerment, ensures equitable income distribution, and creates a highly stable, non-precarious labor environment that reverses rural-to-urban migration.

In a typical GOAZ ecosystem, the goal is to generate direct employment for 1,000+ people across modern greenhouse facilities, processing and packaging plants, administrative units, and other related operations. Additionally, GOAZ serves as a hub for numerous supporting industries, including fertilizer producers, the plastics and wood sectors, construction, and landscaping. This helps revitalize cash flow and prosperity in the local economy in multiple ways, and as a result, slows the trend of rural-to-urban migration (TTB, 2020-2025).

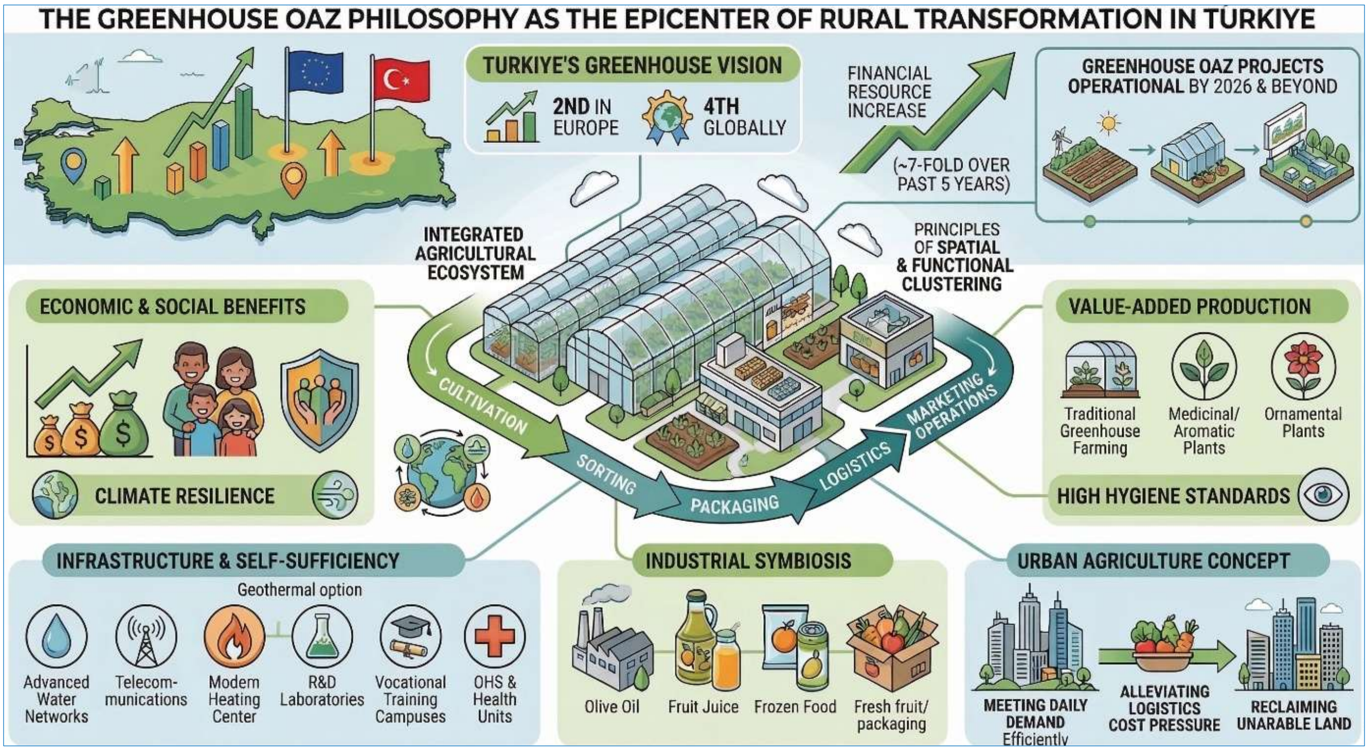

Fig. 5. The GOAZ philosophy as the epicenter of rural transformation in Turkiye

2.5. Sustainability Vision and Global Market Integration

The GOAZ model, which focuses on fighting environmental crises (Ngirubiu et al., 2026), operates under the "Green Agricultural Zone" identity and fully aligns with the principles of the European Green Deal (Esenlikci, 2023; Ataseven, 2023; Işık et al., 2023). In facilities that strictly follow circular economy principles, wastewater reprocessing, the conversion of organic waste into energy at biogas and biomass plants, and zero-waste targets are systematically enforced. This strong physical and technological infrastructure accelerates investors' attainment of Good Agricultural Practices (GAP) certifications, leading to a significant improvement in both the quality and quantity of product supply (TTB, 2020-2025) (Fig. 3).

In the international trade sector, the GlobalGAP certification, which is essential for exporting in line with EU standards, is readily achieved through the controlled production processes within the GOAZ framework. This system, which uses Integrated Crop Management (ICM) and Integrated Pest Management (IPM) techniques, guarantees careful monitoring of numerous mandatory and recommended compliance standards. The collaborative nature of the production process reduces logistics costs, while the high-quality standards set by this system allow producers to brand their products and sell them at their true value (Fiankor et al., 2020; Githiga et al., 2024; Li et al., 2025).

Crucially, this zero-emission profile transforms environmental compliance into a tangible financial asset. By eliminating fossil-fuel-based heating, GOAZ operations generate substantial carbon credits, which can be monetized in international voluntary carbon markets, establishing an additional, highly lucrative revenue stream for the project developers.

3. The Mega-Scale Case Study: Empirical Evidence from Turkiye

An examination of Turkiye's agricultural vision reveals that the country ranks second in Europe and fourth globally in the greenhouse sector, after Spain, thereby underscoring its expertise and infrastructure potential in this field (Gürpınar and Aktürk, 2023; Kapur et al., 2024; Özkan, 2024). In line with the approximately sevenfold increase in financial resources allocated to the sector over the past five years, numerous GOAZ projects across the country have entered the construction or planning phase; regions where feasibility studies have been completed and are awaiting inclusion in investment programs are projected to become operational by 2026 and beyond (Fig. 5). In addition, numerous GOAZ and

Geothermal GOAZ projects have been prepared and are awaiting approval (TTB, 2020-2025).

3.1. The Development Process of GOAZs

The "Regulation on Agriculture-Based Specialized Organized Industrial Zones," which marked the first step in creating GOAZs in Turkiye, was published in 2017. In 2022, some amendments were made to the regulation to address issues encountered during its implementation. The legal and operational foundation of GOAZs is firmly embedded in Turkiye's National Strategic Development Plans (TTB, 2020-2025). Rather than isolated agricultural initiatives, these zones are designated as sovereign macroeconomic priorities to exponentially increase sustainable crop production, ensure food security, and develop high-value-added agricultural-industry integration.

By institutionalizing this clustering model within national regulatory frameworks, the state provides long-term sovereign support for both domestic and international investors, thereby substantially mitigating political and operational risks while facilitating the modernization of greenhouse infrastructure and the development of large-scale facilities through significant public subsidies.

Fig. 6. GOAZ: A smart and sustainable organic farming region ecosystem

Under the Eleventh Development Plan's provision that states, "In addition to the construction of modern greenhouses for protected cultivation, investment and operational financing support will be provided for the modernization, expansion, and construction of packaging facilities and storage facilities for existing greenhouses," a measure has been introduced. This measure includes the development of the "Greenhouse Infrastructure Development Project," which aims to identify suitable areas for modern greenhouse farming and establish the necessary infrastructure to encourage investment. The project focuses on adapting land infrastructure in selected locations on state-owned and pasture lands in inland regions and areas with geothermal resources, making them suitable for greenhouse farming. It also seeks to address the shortfall in agricultural supply during critical seasons and to facilitate production planning.

In 2019, the government allocated financial resources to 14 provincial governors' offices to conduct feasibility studies for GOAZs, prepare infrastructure projects, and determine the infrastructure cost budget (TTB, 2020-2025). The development process of GOAZs in Turkiye over the years is shown in Fig. 7 and Table 1.

By the end of 2025, the number of GOAZs with legal-entity status in Turkiye had increased to 24 (Fig. 2 and Tables 2–3). Crop production is currently happening in four GOAZs: two GOAZs (Çaycuma and Bafra) and two Geothermal GOAZs (Sarayköy and Efeler), while efforts to start production in the remaining GOAZs continue.

3.2. Spatial Planning

The fundamental prerequisite for building a sustainable competitive advantage at the sector level is to design the spatial organization of production factors in perfect harmony (Lu et al., 2023; Xu and Zhang, 2023; Hao et al., 2025). The topographic layout of GOAZ includes key arteries such as greenhouse areas, industrial facilities, administrative units, technical infrastructure, green belts, and logistics centers (Fig. 8). At least 8% of the total planned area must be allocated to common-use zones, including administrative and social services, roads, wastewater treatment systems, and active green spaces; meanwhile, at least 5% should be designated for industrial parcels where crops are transformed into value-added final products (Fig. 9). Setting the minimum greenhouse area at 10,000 m² (10 decares) ensures rational and profitable production by creating a strong economy of scale and eliminating inefficiencies related to small-scale operations (minimum greenhouse area of 5 decares) (TDİOSB, 2017). The architectural and spatial design of GOAZs is strictly governed by national specialized industrial zoning legislations. This statutory compliance ensures that all infrastructural elements ranging from centralized geothermal distribution networks to wastewater treatment and green zones strictly adhere to premium agro-industrial and environmental standards.

Fig. 7. Development of GOAZs in Turkiye by year (see Table 1)

To establish the ownership structure of GOAZs, at least 75% of the selected land must be state-owned; the remaining privately owned properties are expropriated after the zone acquires legal personality, ensuring the area's integrity. No such requirement exists for Geothermal GOAZs (TDİOSB, 2017).

3.3. Legal Entity Building, Financing Solutions and State Incentives

The governance framework of GOAZs is fundamentally a robust Public-Private Partnership (PPP) model. By systematically integrating local state authorities, chambers of industry and commerce, and private enterprises into a unified legal entity, the model establishes a highly secure and sovereign-backed administrative structure. This PPP approach minimizes bureaucratic bottlenecks through "One-Stop Office" solutions and creates a highly 'bankable' environment, making it an ideal framework for international financial institutions (e.g., World Bank, EBRD) to deploy green infrastructure and regional development funds. GOAZ projects in Turkiye are executed under the oversight of the Ministry of Agriculture, within the scope of zoning approval and inspection processes.

Typically, for a project to start, at least one of the region's chambers of industry or commerce must participate as a founding member. Depending on demand, local authorities (such as governor's offices and municipalities) and professional associations or unions, like agricultural chambers, may also be involved in this initiative. Additionally, these projects can be established by private companies and individuals (Fig. 10) (TDİOSB, 2017). Regarding financing strategies, the Ministry of Agriculture offers highly flexible credit options for expropriation costs, engineering planning, and infrastructure construction. These loans, which vary according to the region's level of economic development, are available at interest rates of 1% over a 15-year term in priority regions, 2% over a 13-year term in standard provinces, and 3% over an 11-year term in developed provinces. In the loan approval process, allocated GOAZ lands or the cash/real estate assets of the founding institutions may be used as collateral (TRGM, 2024).

To heavily subsidize Capital Expenditures (CAPEX), the government provides long-term, low-interest financing through state-backed agricultural development banks and national green grant programs. Furthermore, to eliminate bureaucratic friction and accelerate project deployment, a centralized 'One-Stop Office' framework has been established (Fig. 10) (TTB, 2020-2025). This executive mechanism enables international and local investors to seamlessly manage all permitting, licensing, and infrastructure utility connections (geothermal, electricity, water, and waste management) through a single governing body, ensuring a frictionless, turnkey investment environment.

Table 1. The development process of GOAZs in Turkiye (TTB, 2020-2025)

Year	Development
2017	Publication of the “Regulation on Agriculture-Based Specialized Organized Industrial Zones”
2019	The allocation of government funds to 14 provincial governors’ offices to carry out work on preparing the “Greenhouse Infrastructure Development Project,” conducting feasibility studies for GOAZs, preparing infrastructure projects, and determining the infrastructure cost budget.
2020	Commencement of infrastructure construction (roads, drinking and utility water, sewerage, stormwater, electricity, etc.) for the Sarayköy (Denizli) Geothermal GOAZ. Conducting feasibility studies for the Dikili (İzmir) Geothermal GOAZ, Edremit (Balıkesir) Geothermal GOAZ, Çay (Afyonkarahisar) Geothermal GOAZ, Kocasinan (Kayseri) Geothermal GOAZ, Banaz (Uşak) Geothermal GOAZ, Karataş (Adana) GOAZ, Bayındır (İzmir) GOAZ, and Kınık (İzmir) GOAZ.
2021	The allocation of greenhouse production and industrial parcels within the Sarayköy (Denizli) Geothermal GOAZ, where infrastructure work has been completed, to investors/producers, and the commencement of construction of modern greenhouses by these investors/producers. Commencement of infrastructure construction for the Bafra (Samsun) Greenhouse OAZ, the Çaycuma (Zonguldak) GOAZ, and the Diyadin (Ağrı) Geothermal GOAZ. Completion of site selection and establishment of legal entities for Bayındır (Izmir) GOAZ, Kınık (Izmir) GOAZ, Karataş (Adana) GOAZ, Edremit (Balıkesir) Geothermal GOAZ, Efeler (Aydın) Geothermal GOAZ, Simav (Kütahya) Geothermal GOAZ, and Dikili (Izmir) Geothermal GOAZ. Preparation of general layout, zoning, and parceling plans, and conduct of feasibility studies for the Yazıhan (Malatya) GOAZ.
2022	To address shortcomings identified in practice, certain amendments were made to the “Regulation on Agriculture-Based Specialized Organized Industrial Zones,” published in 2017. Commencement of production at the Sarayköy (Denizli) Geothermal GOAZ. Completion of infrastructure works at the Diyadin (Ağrı) Geothermal GOAZ, Bafra (Samsun) GOAZ, and Çaycuma (Zonguldak) GOAZ, and allocation of greenhouse and industrial parcels to investors/producers. Commencing infrastructure construction at the Dikili (Izmir) Geothermal GOAZ. Launching the implementation of the “Turkiye Climate-Smart and Competitive Agricultural Growth Project” (TUCSAP) by the Ministry of Agriculture and the World Bank. Within the scope of the project, the selection of the Dikili (Izmir) Geothermal GOAZ as a pilot project and the provision of $65 million in financing by the World Bank. Completion of the investment analysis for the Gönen (Balıkesir) Geothermal GOAZ, which will utilize four renewable energy sources (geothermal, solar, wind, and biomass). Expropriation work has begun for the Simav (Kütahya) Geothermal GOAZ. Feasibility studies for the Karataş (Adana) GOAZ, Bayındır (İzmir) GOAZ, and Yazıhan (Malatya) GOAZ have been completed. Approval of the master plan and infrastructure module projects for the Efeler (Aydın) Geothermal GOAZ. Acquisition of legal entity status by the Kozaklı (Nevşehir) Geothermal GOAZ, and completion of project and feasibility studies. Finalization of the site selection for the Karkın (Aksaray) and Kocasinan (Kayseri) Geothermal GOAZ projects. Continuation of the site selection study for the Ayvacık (Çanakkale) Geothermal GOAZ.
2023	Approval by the World Bank of the feasibility report for the Dikili (Izmir) Geothermal GOAZ. Inclusion of the Kozaklı (Nevşehir) Geothermal GOAZ and the Karataş (Adana) GOAZ in the investment program.
2024	Completion of the Environmental and Social Impact Assessment report for the World Bank-funded Dikili (Izmir) Geothermal GOAZ. Commencement of infrastructure construction for the Dikili (Izmir) Geothermal GOAZ, Karataş (Adana) GOAZ, and Bayındır (Izmir) GOAZ. Completion of the projects for the Karataş (Adana) GOAZ, Kocasinan (Kayseri) Geothermal GOAZ, Karkın (Aksaray) Geothermal GOAZ, and Gönen (Balıkesir) Geothermal GOAZ. The establishment of legal entities for the Silopi (Şırnak) GOAZ, Banaz (Uşak) Geothermal GOAZ, Bigadiç (Balıkesir) Geothermal GOAZ, and Çay (Afyon) Geothermal GOAZ.
2025	The acquisition of legal personality by the Yerköy (Yozgat) Geothermal GOAZ and the Batman GOAZ. The number of GOAZs that have acquired legal personality across Turkiye was rising to 24. Continuing of crop production at four GOAZs, two GOAZs (Çaycuma and Bafra) and two Geothermal GOAZs (Sarayköy and Efeler), and activities for starting production at other 20 GOAZs that have obtained legal personality.

3.4. Infrastructure Costs and Financing Model

The first and largest fixed investment item in implementing a GOAZ project is infrastructure work (Fig. 11). Following the establishment of the legal entity, the necessary feasibility studies, engineering, and planning expenses are financed through contributions from the founding partners. Various internal and external financing alternatives may also be evaluated to enable a loan application to the Ministry for the project’s exploration costs and general administrative expenses. Interest-subsidized loans provided by the Ministry of Agriculture can be converted into grants at an 80% rate if conditions such as the project’s inclusion in the investment program and the allocation of land at a reduced rate are met. The infrastructure investments for GOAZ projects are quite extensive. This includes land acquisition, road construction, drinking water, irrigation, and wastewater networks, as well as electricity, telecommunications, natural gas, drainage systems, and geothermal heating networks, all of which will be directly connected to the greenhouses. Additionally, superstructure elements such as administrative and social buildings and heating centers, as well as necessary drilling works, are included in the cost breakdown. An analysis of current practices in Turkiye reveals that 98% of the investment is directed toward infrastructure construction.

The remaining 1% of the budget is allocated to shared superstructure construction (excluding greenhouses and industrial parcels financed by the investors themselves), 0.5% to land acquisitions, and the final 0.5% to feasibility studies and design services. All of these investment items are covered by payments for the allocation of greenhouse and industrial plots, loans from the Ministry of Agriculture, and dues calculated based on the land owned by members/investors.

Table 2. GOAZs currently in operation or in the process of becoming operational in Turkiye (9 in total) (see Fig. 2) (Compiled from the websites and activity reports of the Ministry of Agriculture and the GOAZs)

No	GOAZ Name (Province)	Actual Situation	Total Area (decare)	Estimated Agricultural Production Capacity[a] (tons/year)	Estimated Infrastructure Investment[b] (million US $)	c) Estimated Superstructure Investment[c] (million US $)	d) Estimated Contribution to the Country's Economy[d] (million US $/year)	Estimated Employment[e] (people)	Website
A	Çaycuma (Zonguldak)	In operation (active)	520	10 000	10	15	15	350	https://caycumaseraosb.org.tr/
B	Bafra (Samsun)	In operation (active)	1190	20 000	20	35	30	800	https://www.seraosb.com/
C	Bayındır (İzmir)	Infrastructure is being prepared	892	15 000	15	30	20	600	https://bayindirtdiosb.org.tr/
D	Karataş (Adana)	Infrastructure is being prepared	2852	45 000	50	90	70	1900	
E	Silopi (Şırnak)	Infrastructure is being prepared	947	15 000	15	30	20	650	
F	Kınık (İzmir) (Seeds, Seedlings, Aromatic Plants)	Infrastructure is being prepared	1230	20 000	20	40	30	800	https://kiniktdiosb.org.tr/
G	Yazıhan (Malatya)	In the planning phase	890	15 000	15	30	20	600	
H	Batman	In the planning phase	1110.7	20 000	20	35	30	750	
I	Yalova (Floristry)	In the planning phase	1030	15 000	15	30	20	700	
Total			**10 661**	**170 000**	**180**	**335**	**255**	**7150**	
Average			**1185**	**18 900**	**20**	**37.2**	**28.3**	**800**	

[a] Based on the layout plans in the feasibility reports of GOAZs, an average of 15-20 tons per decare was assumed.
[b] Based on the layout plans in the feasibility reports of GOAZs, $1 million was assumed for 1,000 tons of crop production.
[c] Based on the layout plans in the feasibility reports of GOAZs, the estimated infrastructure investment has been set at 1.5 to 2 times the amount.
[d] Based on the layout plans in the feasibility reports of GOAZs, the cost for 1,000 tons of crop production has been set at 1.5 to 2 million dollars.
[e] Calculated as the total area of GOAZs (decares) multiplied by 0.7 people.

Table 3. Geothermal GOAZs currently in operation or in the process of becoming operational in Turkiye (15 in total) (see Fig. 2) (Compiled from the websites and activity reports of the Ministry of Agriculture and the Geothermal GOAZs)

No	Geothermal Greenhouse OAZ Name (Province)	Actual Situation	Total Area (decare)	Greenhouse Production Area[a] (decare)	Installed Capacity[b] (MWt)	Greenhouse Area (number)	Industrial Area (number)	Estimated Agricultural Production Capacity[c] (tons/year)	Estimated Infrastructure Investment[d] (million US $)	Estimated Superstructure Investment[e] (million US $)	Estimated Contribution to the Country's Economy[f] (million US $/year)	Estimated Permanent Employment[g] (people)	Website
1	Sarayköy (Denizli)	In operation (active)	729.0	382.0	76.4	12	2	15,000	15	30	20	600	
2	Efeler (Aydın)	In operation (active)	717.3	400.0	80.0	20	9	15,000	15	30	20	600	
3	Diyadin (Ağrı)	Infrastructure is being prepared	1,290.0	800.0	160.0	35	2	30,000	30	60	40	1,200	http://www.diyadintdiosb.org.tr/
4	Dikili (İzmir)	Infrastructure is being prepared	3,037.0	1,432.0	286.4	50	47	50,000	55	110	70	2,100	https://www.dikilitdiosb.org.tr/
5	Simav (Kütahya)	Infrastructure is being prepared	1,185.0	662.8	132.6	44	16	25,000	25	50	35	1,000	https://simavtdiosb.org.tr/
6	Kocasinan (Kayseri)	Infrastructure is being prepared	1,227.0	480.0	96.0	40	9	15,000	20	40	15	750	https://kayseritdiosb.org/
7	Gönen (Balıkesir)	Infrastructure is being prepared	8,000.0	3,192.0	638.4	120	93	110,000	125	250	175	4,750	https://gonentdiosb.org.tr/
8	Edremit (Balıkesir)	Infrastructure is being prepared	640.5	272.0	54.4	21	29	10,000	10	20	15	400	
9	Bigadiç (Balıkesir)	Expropriation is being carried out	2,320.0	576.0	115.2	51	16	20,000	25	50	35	850	https://www.bigadictdiosb.org.tr/
10	Karkın (Aksaray)	Expropriation is being carried out	1,440.0	600.0	120.0	30	17	20,000	25	50	35	900	https://aksaraytdiosb.org.tr/
11	Kozaklı (Nevşehir)	In the planning phase	1,362.0	667.4	133.5	32	13	25,000	25	50	35	1,000	https://nevsehirtdiosb.org.tr/
12	Ayvacık (Çanakkale)	In the planning phase	2,400.0	1,070.4	214.1	48	19	35,000	45	90	50	1,600	https://canakkaleayvaciktdiosb.org.tr/
13	Çay (Afyon)	In the planning phase	2,979.0	1,730.4	346.1	32	12	60,000	70	140	85	2,600	https://www.afyonotb.org.tr/
14	Banaz (Uşak)	In the planning phase	2,352.0	1,184.0	236.8	25		40,000	45	90	65	1,750	https://banazotb.org.tr/
15	Yerköy (Yozgat)	In the planning phase	1,125.7	795.2	159.0	30		25,000	30	60	40	1,200	https://yerkoytdiosb.org.tr/
		Total	30,805.0	14,245.0	2,848.9	500		495,000	560	1,120	735	21,300	
		Average	2,054.0	949.6	189.9	39		33,000	37.3	74.6	49	1,420	

[a] The greenhouse production area constitutes 80% of the greenhouse area in the GOAZ planning (in the GOAZ feasibility reports, the production area of a geothermal greenhouse is 80% of the total greenhouse area).
[b] MWt values were calculated based on the assumption that 1 MWt of power is required to heat 5 decares of greenhouse production area (Çelmen et al., 2025; they stated that 1 MWt of power is required to heat 5 decares of greenhouse production area).
[c] Calculated as total greenhouse production area (decares) × 35 tons (According to data published by the Turkish Ministry of Agriculture, the annual tomato production per decare of greenhouse production area is 35 tons/decare. Tomatoes were selected as the reference crop because they account for 96.45% of the total vegetable production in geothermal greenhouse operations in Turkiye).
[d] Calculated as total greenhouse production area (decares) × $40,000 (The infrastructure cost for a geothermally heated high-tech greenhouse, as published by the Turkish Ministry of Agriculture, is $40,000 per decare).
[e] Calculated as total greenhouse production area (decares) × $80,000 (the infrastructure cost for geothermally heated high-tech greenhouses, as published by the Turkish Ministry of Agriculture, is $80,000 per decare).
[f] Total production capacity (tons) × $1,400 (approximate revenue per ton) (The annual average selling price of 1 ton of tomatoes produced in a geothermally heated high-tech greenhouse, as published by the Turkish Ministry of Agriculture, is $1,400. Tomatoes were selected as the reference product because they account for 96.45% of total vegetable production in geothermal greenhouse operations in Turkiye).
[g] Greenhouse production area (decare) x 1.5 people (According to Geothermal GOAZ feasibility reports, the estimated employment in a geothermal greenhouse is 1.5 people per decare).

3.5. Revenue Streams and Commercial Monetization Strategy

The operational financial architecture of GOAZs is structured around highly diversified and resilient revenue streams, ensuring long-term commercial viability. The primary capital recovery mechanism is the premium leasing and sale of high-tech greenhouse and industrial parcels, which directly offsets initial infrastructure loans.

Furthermore, the model generates perpetual operational income through decentralized utility management, monetizing the distribution of industrial water and telecommunications, and, specifically, the metered sale of geothermal heat energy to individual producers. This diversified monetization strategy insulates the central governing entity from single-market shocks and guarantees sustained positive cash flow (Fig. 12).

In addition to land sales, other operating revenues that support the facility's sustainability include sales and distribution of water and electricity, rental fees, management fees, and profits from geothermal heat sales. These integrated facilities cater to a very broad audience. While fresh produce growers, logistics companies, and the local community are at the heart of the project, European countries and densely populated, developed local cities are the primary targets for marketing the final products. In particular, the growing global demand for healthy food and fresh agricultural products in the post-pandemic era has further highlighted the strategic importance of these projects, which center on good agricultural practices. Market instability caused by fluctuations in input costs, particularly energy prices, can be mitigated by using geothermal resources, enabling the establishment of a stable pricing policy.

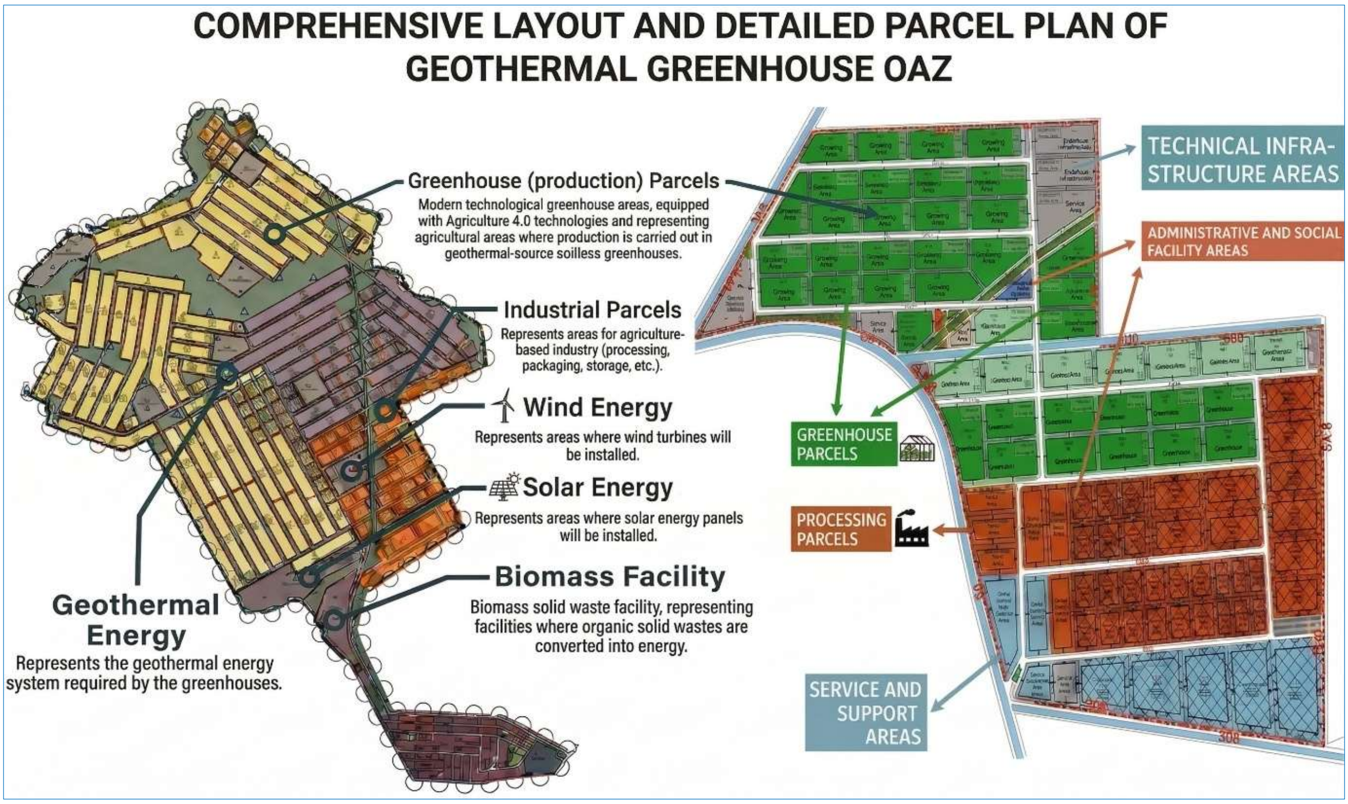

Fig. 8. The main components of GOAZs

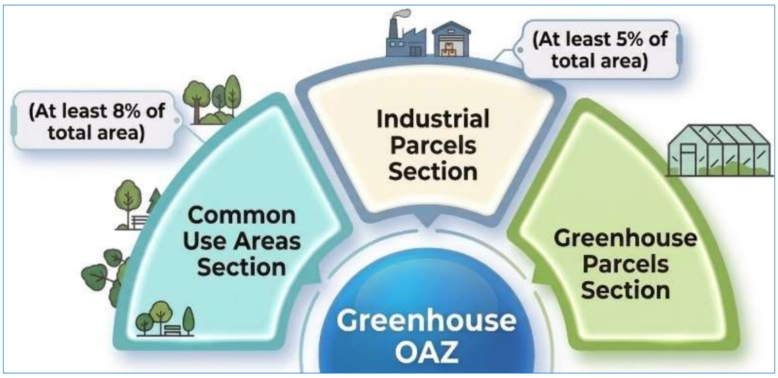

Fig. 9. Minimum requirements for the total area of a GOAZ

Fig. 10. Legal entity building, financing solutions and state incentives of GOAZs

3.6. Land Allocation and Market Demand

The successful implementation of a GOAZ project depends on institutional structure, financial support, and a robust technical infrastructure. Significant incentives are offered to investors regarding land acquisition. Geothermal GOAZs are exempt from the requirement that 75% of the land must be state-owned, which is typically a condition for GOAZ applications.

A critical pillar of the model's 'bankability' is the robust incentive structure provided for land acquisition and operational taxes. By acquiring state-owned land and allocating it to qualified investors at an 80% subsidy, the government drastically reduces upfront land CAPEX. Investors receive parcels fully equipped with all infrastructure, including roads, water, electricity, telecommunications, and geothermal connections, which are managed exclusively by the GOAZ Directorate.

Furthermore, the operational phase is heavily de-risked through comprehensive 'tax holidays,' including permanent property tax exemptions, VAT exemptions for machinery, and the waiving of solid waste and municipality fees. This aggressive sovereign subsidization accelerates the construction phase to an average of six months and ensures a highly rapid Return on Investment (ROI). These attractive conditions have led to parcels in the 24 different GOAZ projects across Turkiye being completely sold out by the end of the first year. In cases where demand exceeds capacity, parcel allocation is managed through an auction system. Entrepreneurs who receive their parcels are expected to begin production within two years at the latest.

3.7. Optimization of Geothermal Infrastructure and Drilling Costs

The integration of geothermal energy into greenhouse heating systems enables the efficient use of even low-temperature hydrothermal fluids and the Earth's natural heat, thereby driving a strategic transformation in agricultural production and ending dependence on fossil fuels (Rosas-Casals et al., 2022; Zhu et al., 2022; Carotti et al., 2023; Shortall et al., 2024; Apostolopoulos et al., 2026), and reducing production costs (Kurpaska et al., 2021; Lee et al., 2025; Du et al., 2026).

Geothermal GOAZs present a highly efficient and systematic economic model for regional development and food security. In particular, the good agricultural practices implemented at these facilities are strategically important for public health and access to healthy food. These modern production facilities provide investors with a strong competitive edge and lasting brand value. Geothermal GOAZs do not rely solely on geothermal resources; by integrating with solar, wind, and biomass power plants, they establish a continuous, hybrid energy self-sufficiency system. This stable climate control, achieved through direct hot water lines or advanced geothermal heat pumps, ensures that agricultural productivity remains at its peak throughout the year (TTB, 2020-2025).
Undoubtedly, the most important factor affecting the profitability of greenhouse farming is the cost of heating and cooling (Boyacı et al., 2025; Dimitropoulou et al., 2025; Şirikçi and Çetinkaya, 2025). In traditional greenhouse operations, high heating costs-particularly on cold days-force producers to plant only in spring and fall for economic reasons (Boyacı et al., 2025). This seasonal constraint reduces the volume of fresh produce available during transitional months, setting the stage for sudden spikes in consumer prices (Dimitropoulou et al., 2025).

Eco-friendly, low-temperature geothermal resources, when combined with climate-control technologies, enable uninterrupted greenhouse production year-round. This technological transformation contributes to market stability by preventing seasonal supply shortages and associated price fluctuations, while also increasing yield per unit area by up to tenfold compared to conventional methods. The resulting increase in crop yield and the radical reduction in heating costs provide investors with high competitive strength in international markets and a traceable, reliable brand value. Minimizing energy costs to this extent reduces unit production costs and establishes operations on a financially predictable and reliable foundation (Argento et al., 2024; Boyacı et al., 2025; Dimitropoulou et al., 2025).

Geothermal energy is a broad umbrella term for the natural internal heat generated and stored in the depths of the Earth's crust as a result of magmatic activity and radioactive decay (Fig. 13) (Glassley, 2014). A hydrothermal source is a specific type of geothermal system in which water acts as the transport medium, facilitating the transfer of this heat to the Earth's surface. For an underground geothermal potential to be classified as a "hydrothermal source," it requires not only a high-temperature heat source but also a groundwater (fluid) capable of absorbing this heat and transporting it to the surface, as well as a permeable reservoir structure where the fluid can be trapped and move (DiPippo, 2012).

Fig. 11. All stages in the implementation of a GOAZ project

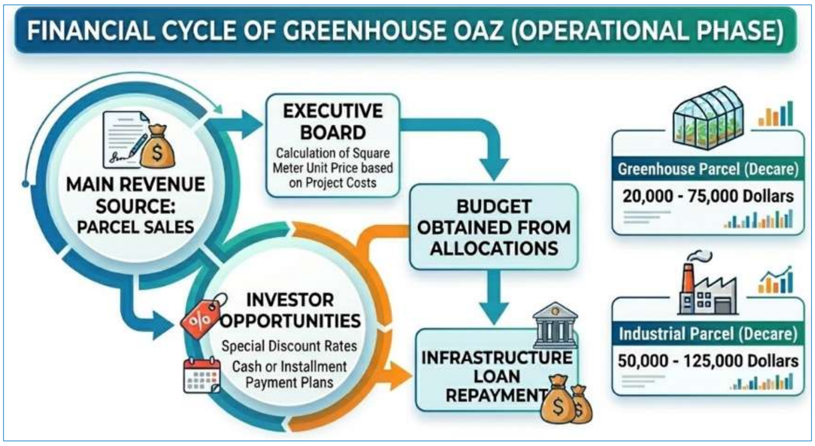

Fig. 12. The financial cycle of GOAZs during the operational phase

In short, while geothermal energy defines the fundamental form of energy (heat) contained within the source, the term "hydrothermal resource" describes dynamic, water-bearing systems where this energy becomes economically exploitable through its transport to the surface via groundwater, a system where the "heat, water, and permeability" triad converges (Barbier, 2002). Geothermal (ground- and water-source) heat pumps are highly energy-efficient, environmentally friendly technologies used for climate control in greenhouses by harnessing the relatively constant thermal energy of the ground year-round.

Compared to traditional fossil-fuel-fired boilers or electric heaters, these systems significantly reduce energy consumption for greenhouse heating and cooling, thereby lowering operating costs, minimizing greenhouse gas emissions such as carbon dioxide, and supporting carbon-neutral, sustainable agriculture (Zhou et al., 2026). With its advanced heat-transfer capacity, this technology can consistently maintain the optimal thermal conditions essential for plant growth within the greenhouse, despite extreme temperature fluctuations in the external environment (Boughanmi et al., 2016).

Although the initial investment costs associated with drilling and installing underground and water heat exchangers are high, the high coefficient of performance (COP) offered by geothermal heat pumps allows the system investment to be recouped quickly; by fulfilling both heating and cooling functions year-round through a single infrastructure, it ensures the long-term net profitability of modern agricultural operations (Seo et al., 2021). Heat pump technologies (ground-source, water-source, and air-source) offer the advantage of providing both heating and cooling from a single central unit due to their system design.

On the other hand, Solar Stirling systems are cogeneration mechanisms that generate electricity from solar energy while simultaneously using the resulting waste heat to support space heating. The integration of these two technologies provides businesses with a highly efficient, hybrid climate-control and energy infrastructure that serves as a backup for the other, depending on climatic conditions and seasonal needs (Bataineh, 2024; Guarino et al., 2021; Du et al., 2026).

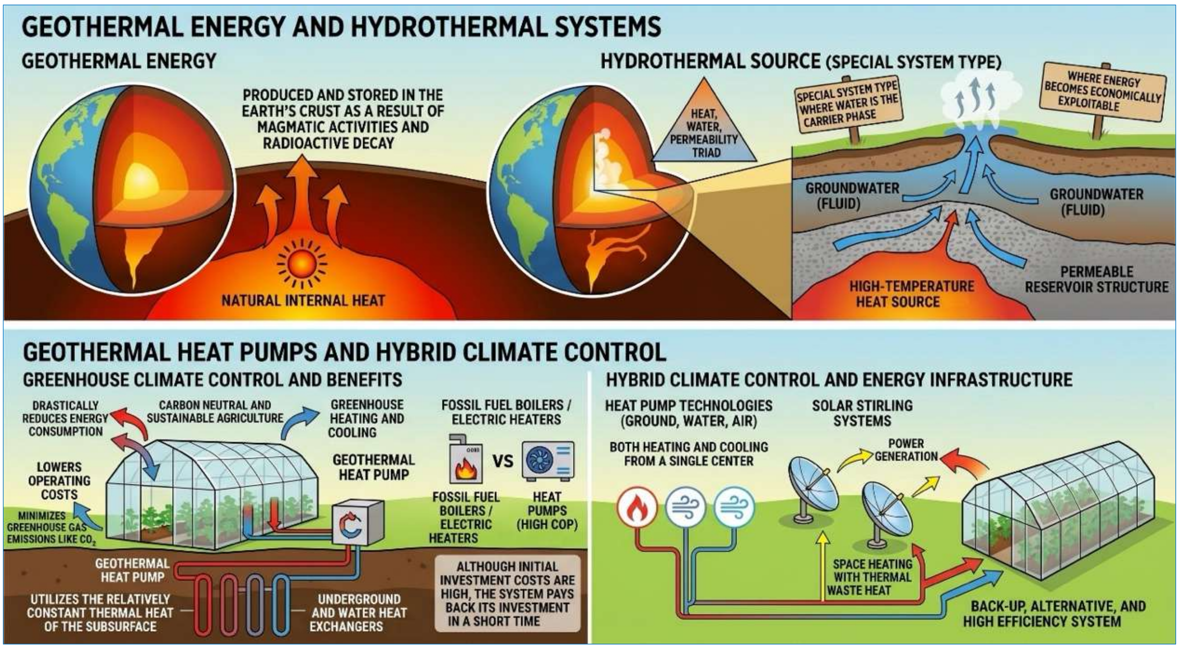

Fig. 13. Types of geothermal energy sources and their use in greenhouses

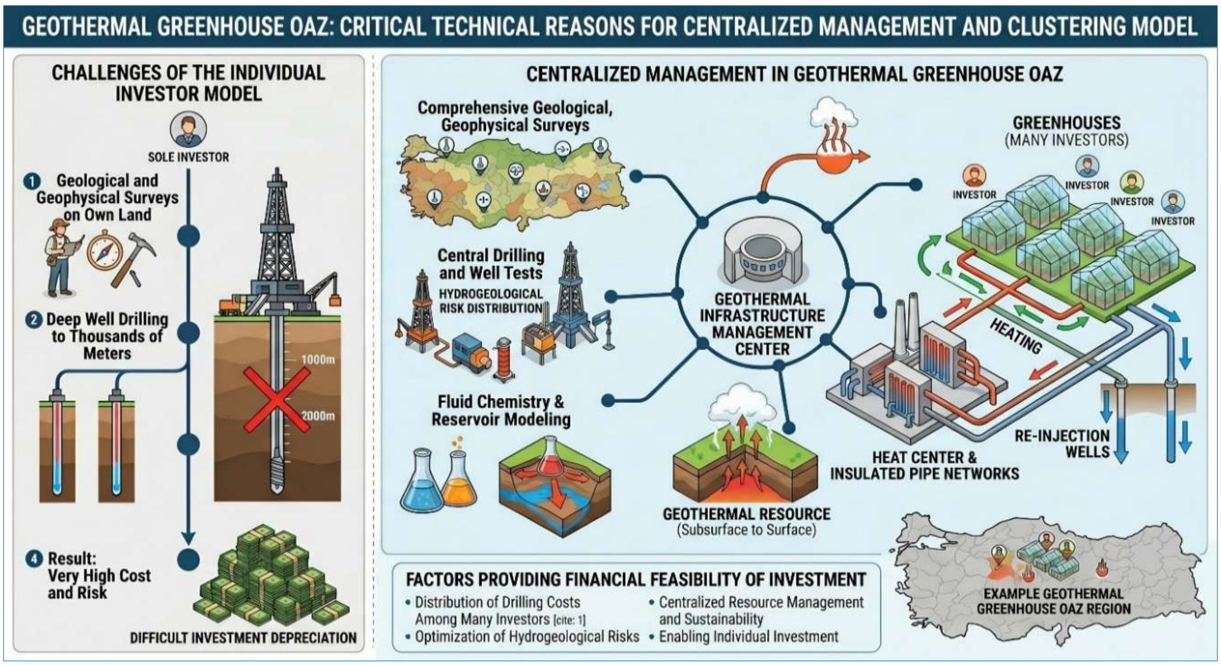

Fig. 14. The key technical reasons for the Geothermal GOAZ cluster model

The high specific heat capacity and thermal inertia of large bodies of water in lakes and seas make these bodies highly efficient thermal reservoirs for heating and cooling greenhouses via geothermal heat pumps (surface water heat pumps). These water bodies, which provide stable temperatures year-round, drastically reduce operational costs and carbon emissions by eliminating dependence on fossil fuels when integrated with heat pumps (Lee et al., 2020; Liew et al., 2021; Pająk et al., 2024).

In addition to seas and lakes, streams and rivers, which have high heat-transfer capacity due to their dynamic flow regimes, can also be successfully integrated into climatic systems using 'river water source heat pumps'. These systems, implemented on a megawatt (MW) scale in district heating networks in Germany (Trabert et al., 2021) and in various European basins such as the Clyde River in Scotland (Ptak et al., 2025), due to their high installation feasibility (Jung et al., 2021), represent a proven strategic alternative for heating agricultural production areas in a sustainable manner independent of fossil fuels.

Geothermal GOAZs reduce dependence on traditional fossil fuels by using low- and medium-temperature geothermal fluids from beneath the surface, significantly reducing production costs. These systems do not rely solely on geothermal energy; they also combine solar, wind, and biomass power plants to create a seamless, hybrid energy self-sufficiency system. Stable climate control, delivered through direct hot-water lines or advanced heat pumps, keeps agricultural productivity at its highest levels year-round (TTB, 2020-2025). The key technical reason for the Geothermal GOAZ cluster model is the geosciences challenges involved in resource exploration and operations. For a single greenhouse investor to carry out geological and geophysical surveys on their own land and then drill production and reinjection of wells to depths of thousands of meters require a very high financial investment.

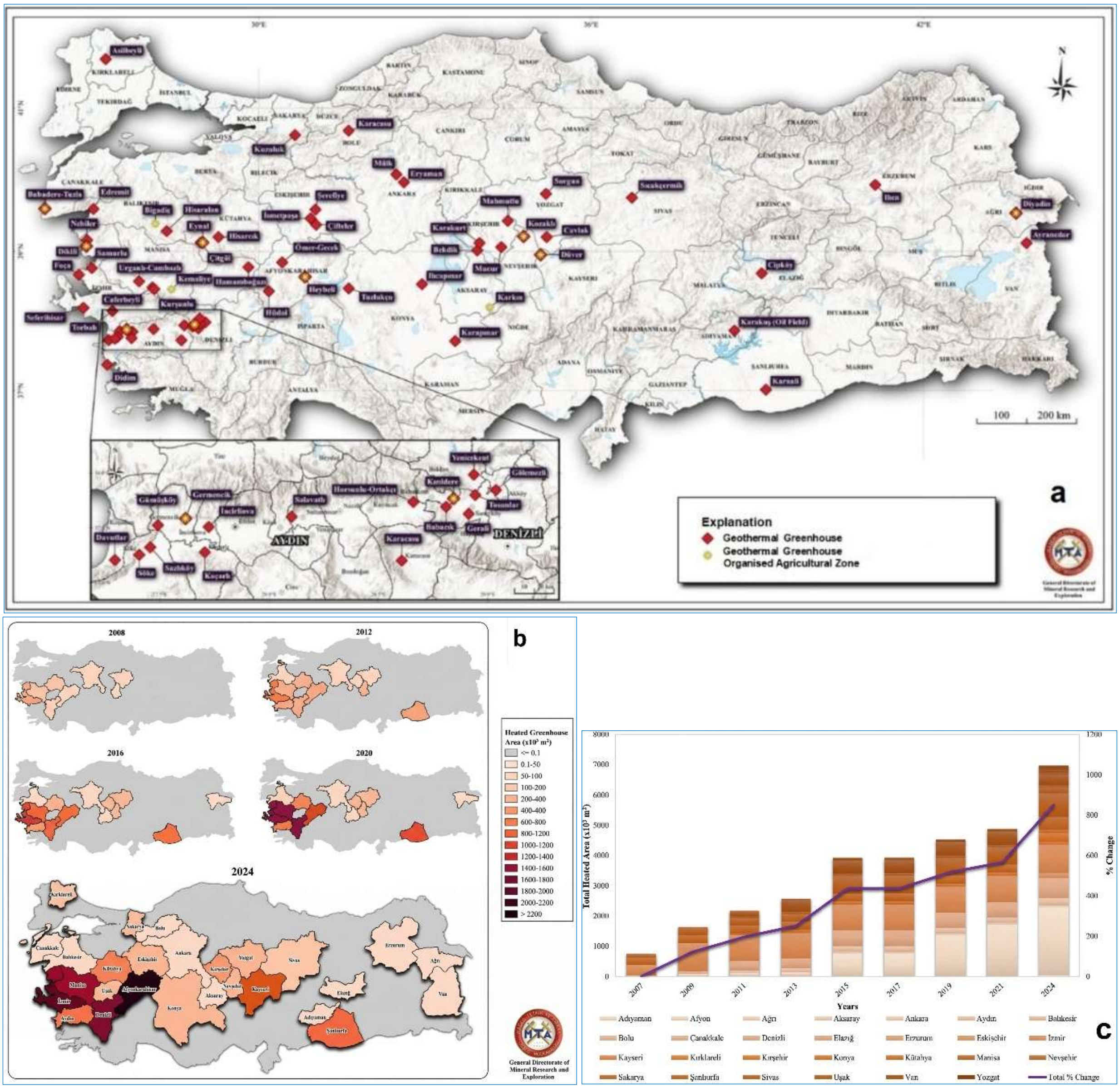

Fig. 15. a. Greenhouses heated by geothermal energy and associated geothermal fields in Turkiye. b. Geographic distribution of geothermal greenhouse heating in Turkiye between 2008 and 2024, c. Development of greenhouse heating by province in Turkiye between 2007 and 2024 (from Çelmen et al., 2025)

In Geothermal GOAZs, however, the management of this geothermal infrastructure is centralized. The region's geothermal fluid potential is evaluated through comprehensive studies (including geological and geophysical exploration, well drilling, well testing, fluid chemistry, and reservoir modeling) conducted by a single authority. The geothermal resources extracted from the subsurface are distributed to greenhouses via a central heat plant and insulated pipe networks (ring network), while the fluid from which heat has been extracted is reinjected back into the reservoir through reinjection wells. The most critical factor affecting investment's financial feasibility is how drilling costs and geothermal hydrogeological risks are shared among a large number of investors (Fig. 14).

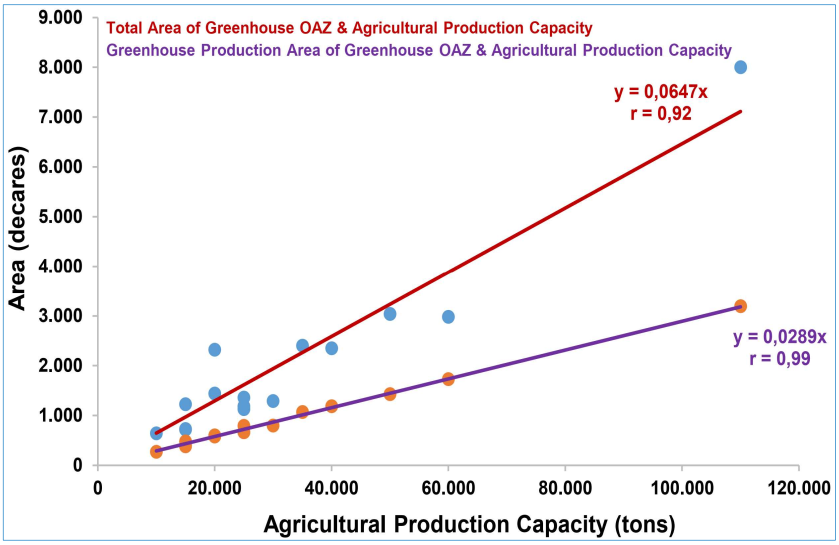

Fig. 16. Relationship between agricultural production capacity and total area and greenhouse area in Geothermal GOAZs (Table 3)

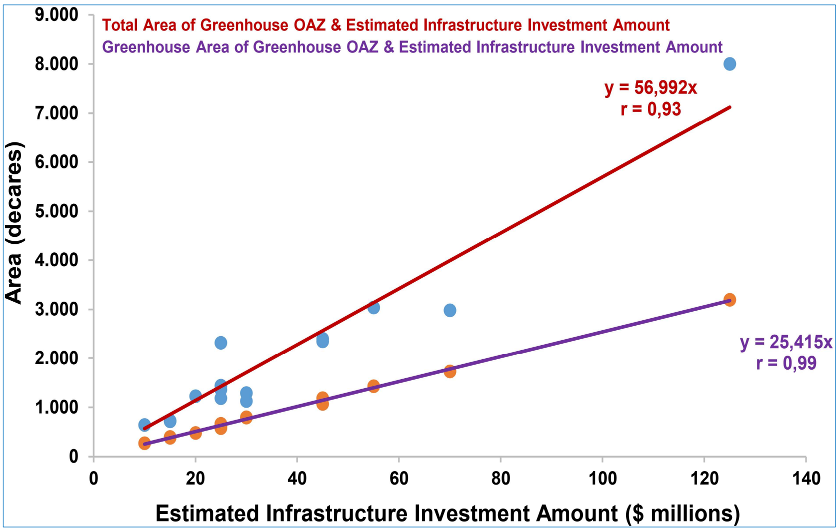

Fig. 17. The relationship between the estimated infrastructure investment amount and the total area and greenhouse production area in Geothermal GOAZs (see Table 3)

GOAZs are primarily established in areas with hydrothermal resources. In areas without hydrothermal resources, GOAZs equipped with geothermal heat pumps can be established to heat the greenhouses. Because geothermal heat pumps extract shallow thermal energy stored in the Earth's crust and integrate it into production systems, GOAZs using this technology also directly benefit from geothermal energy. Accordingly, GOAZs that meet their heating and cooling needs with geothermal heat pumps should be recognized as using this renewable subsurface energy source as their primary energy source and should be evaluated directly as "Geothermal GOAZs" in legal or technical planning processes

Considering that geothermal energy consists of natural heat stored deep within the Earth's crust and hydrothermal systems that transport this heat to the surface via groundwater, ground-source and cold-water-source geothermal heat pumps are also considered systems that directly utilize geothermal energy, as they extract shallow thermal energy stored in the Earth's crust and integrate it into production systems (Haehnlein et al., 2010; Lund and Toth, 2021; Elshehabi and Alfehaid, 2025). Lund and Toth (2021) emphasize that shallow geothermal heat pumps account for the largest share (approximately 58.8%) of the "direct use" of geothermal energy and that these systems directly extract shallow thermal energy from the Earth's crust. Therefore, ground-source or groundwater-source heat pump applications should be classified under the category of direct use of geothermal energy rather than as climatic tool systems. In this regard, it is essential to the sustainability of the resource that heat pump-based greenhouse operations, which, like businesses utilizing deep hydrothermal sources, intensively exploit the thermal balance and heat potential of the subsurface, be required to obtain a geothermal license as part of the planning process. Indeed, this approach is also supported by international platforms. The European Geothermal Energy Council (EGEC, 2022) and projects such as GeoPLASMA-CE (2019) conducted across Europe it is emphasized that the uncontrolled use of ground-source and groundwater-based heat pumps can lead to "thermal anomalies" in groundwater resources, and it is recommended that these systems be subject to a licensing/permit framework established by law.

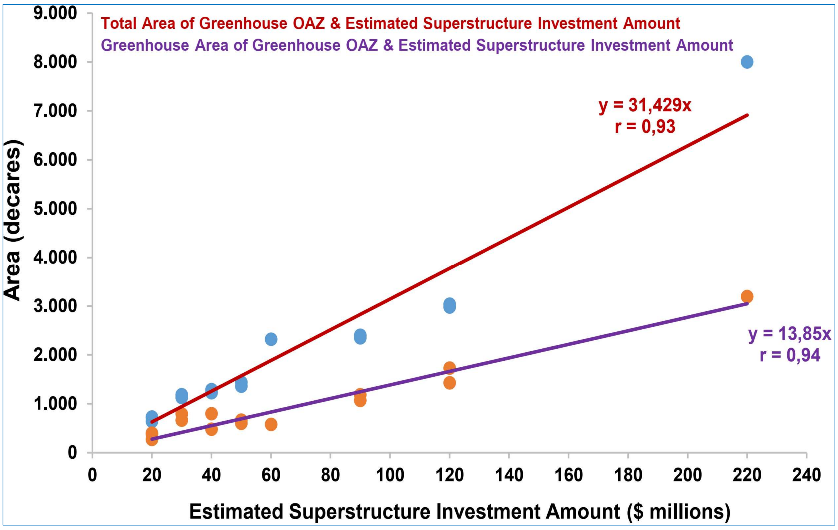

Fig. 18. The relationship between the estimated amount of superstructure investment and the total area and greenhouse production area in Geothermal GOAZs (see Table 3)

4. Engineering Economics of Geothermal GOAZs

While global geothermal energy use (non-electric) is approximately 110,000-120,000 MWt, the share of greenhouse heating is 2-3% (Lund and Toth, 2021; IRENA, 2023a; Şener et al., 2023), averaging 2,875 MWt per 14,375 decares. Analyses show that 1 MWt of power can heat about 5 decares. With an installed capacity of 1,400 MWt (7,000 decares) across 62 sites in 27 provinces of Turkiye, the country accounts for half of the world's geothermal greenhouse heating capacity (Fig. 15) (Çelmen et al., 2025). According to national strategic plans, once current projects (15 Geothermal GOAZs) are fully operational, an additional capacity of 2,849 MWt (14,245 decares) will be added. Turkiye, which will bring its total installed capacity to 4,249 MWt, will significantly increase its global market share and capacity in this sector by heating greenhouses on a scale far beyond the rest of the world combined. Projections suggest that the Turkiye's total geothermal greenhouse potential ranges from 30,000 to 100,000 decares (Kındap, 2023; Şener et al., 2023; Özkan, 2024), indicating strong prospects.

Although the Büyük Menderes and Gediz graben systems are the primary sources of geothermal energy in Turkiye, the Central Anatolia Region's unexploited geothermal potential offers a substantial strategic advantage for large-scale agricultural clustering. The provinces of Central Anatolia offer strategic benefits for integrated geothermal projects due to their abundant sunshine and extensive, flat agricultural lands. In these areas, combining geothermal fluids identified through geological surveys (typically 50-90 °C) with large-scale greenhouse clusters is not just an agricultural effort but also a regional development initiative.

Each Geothermal GOAZ established here will generate a macroeconomic multiplier effect by stimulating a wide network of sectors, from packaging to logistics, beyond direct jobs. Therefore, these regions, where traditional open-field farming is predominant and rural-to-urban migration is ongoing, have the potential to become high-value-added agricultural-industrial hubs.

The relationships between the infrastructure and superstructure investment amounts, greenhouse production areas, economic value added, and employment capacity of Geothermal GOAZs were modeled using statistical regression analysis. The findings have shown that GOAZs are not merely facilities that standardize agricultural productivity; they are also sustainable industrial-agricultural complexes that accelerate regional development, encourage reverse migration to rural areas, and provide high added value to the national macroeconomy.

4.1. Material and Method

Data for the 9 GOAZs and 15 Geothermal GOAZs were compiled from feasibility reports approved by the Turkish Ministry of Agriculture (TTB, 2020-2025). Statistical regression analyses were performed using Microsoft Excel.

Linear regression models were fitted to examine the relationships between the independent variables (e.g., total area, greenhouse production capacity) and the dependent outcome variables (e.g., infrastructure costs, permanent employment, macroeconomic contribution). Correlation coefficients (r) and determination coefficients (R^2) were calculated to determine the strength of the models. Regional climatic correction factors and specific geothermal temperature variations (typically 50-90 °C in Central Anatolia) were treated as constant variables in the feasibility models. The limitation of this study relies on the projected nature of the data for GOAZs currently under construction.

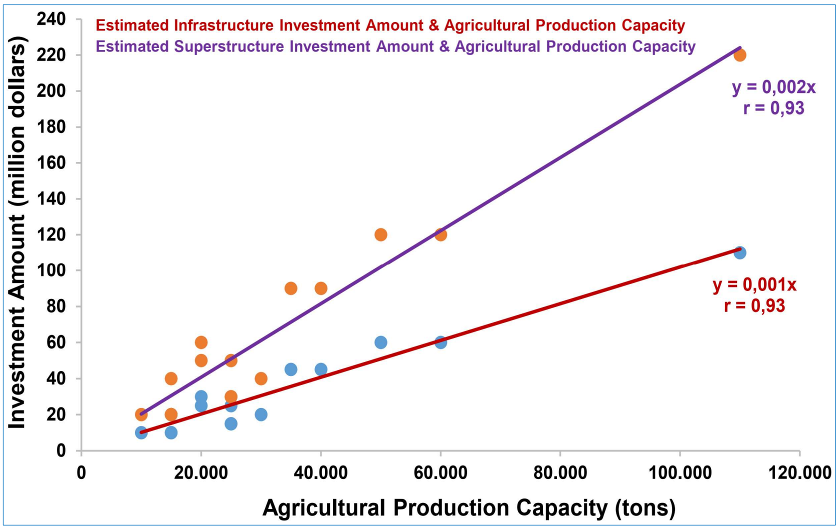

Fig. 19. The relationship between agricultural production capacity and estimated investment amounts in Geothermal GOAZs (see Table 3)

4.2. GOAZ Total Area, Greenhouse Production Area, and Agricultural Production Capacity

In open-field agriculture, due to factors such as climatic shocks, seasonal fluctuations, and soil exhaustion, the relationship between cultivated areas and crop yield is often asymmetrical and unpredictable. In contrast, in fully controlled modern greenhouses heated by geothermal energy, environmental risks are eliminated, and yield per square meter is stabilized year-round and maximized to its biological limits (Carotti et al., 2023; Şirikçi and Çetinkaya, 2025; Boyacı et al., 2025). In large-scale, planned integrated facilities such as GOAZs, the strong positive correlation between greenhouse production area and agricultural production capacity (Fig. 16) demonstrates that expanding the production area enables reliable prediction of capacity growth and return on investment, minimizes investment risk, and ensures food supply security and sectoral competitiveness.

In GOAZ investments, the primary factor determining production capacity is the greenhouse production area. For 1 ton of agricultural production, the project requires 0.0289 decares of greenhouse production area and 0.0647 decares of total area. It is estimated that approximately 35 tons of agricultural production can be achieved annually per 1 decare of greenhouse production area. Accordingly, the answer to the question of how much agricultural product can be produced from a given plot of land is approximately 1 ton per year for each 0.0289-decare greenhouse production area and 0.5 tons per year for each 0.0647-decare total area.

To statistically validate these quantitative thresholds, a linear regression analysis was conducted (Fig. 16). The model demonstrates a highly significant predictive relationship between the greenhouse production area and agricultural capacity ($R^2 = 0.98$, $p < 0.001$). The regression slope confirms the deterministic nature of this relationship, indicating a precise capacity requirement of 0.0289 decares per ton with a narrow error margin (95% CI: 0.0264 - 0.0314). This exceedingly low p-value statistically verifies the clustered GOAZ model's capacity to stabilize yields, eliminating the unpredictability inherent in traditional, fragmented agriculture.

4.3. Infrastructure and Superstructure Investment Costs

In geothermal greenhouse investments, capital-intensive fixed infrastructure costs such as deep drilling, the extraction of thermal fluid to the surface, and the installation of main transmission lines must be incurred regardless of the project's surface area. Consequently, in small, dispersed geothermal greenhouse investments, economies of scale do not operate, causing the cost burden per unit of production capacity (tons) and per unit of area (decares) to rise to unsustainable levels. In contrast, in large-scale, centrally heated integrated agricultural clusters, these very high fixed infrastructure costs are distributed homogeneously across a large production volume, thereby exponentially increasing the financial feasibility of the investment and unit profitability (Lund and Toth, 2021; Karytsas et al., 2022; Carotti et al., 2023; Rezaei et al., 2024)

Recent techno-economic data indicate that costs for independent and small-scale geothermal greenhouses impose a much heavier commercial burden than those of clustered structures (Carotti et al., 2023; IRENA, 2023a; Rezaei et al., 2024). While infrastructure investments for greenhouse production areas in GOAZs amount to approximately \$40,000 per decare (Fig. 17), for small and dispersed greenhouse production areas, the same drilling and infrastructure costs are spread over a smaller area, resulting in a cost range of $120,000 to $150,000 per decare (Carotti et al., 2023; Rezaei et al., 2024). While the superstructure cost per decare of greenhouse production area in GOAZs is $70,000 (Fig. 18), the cost of the superstructure (greenhouse construction, climate control, and automation) in small-scale greenhouses ranges from $95,000 to $110,000 per decare (Carotti et al., 2023; Rezaei et al., 2024).

In large-scale integrated systems such as GOAZ, a total investment of $3,000 is projected for a 1-ton agricultural production capacity, comprising an average of $1,000 for infrastructure and $2,000 for superstructure (Fig. 19). In small-scale and scattered greenhouse investments, however, the infrastructure investment for a 1-ton production capacity rises to the $3,500 to $4,500 range, making even the heating equipment the primary investment item; while the superstructure investment rises to $2,800 to $3,500, resulting in a total investment of $6,300 to $8,000 per ton of agricultural production capacity (Carotti et al., 2023; Rezaei et al., 2024). Based on infrastructure and superstructure investment costs, it demonstrates that large-scale, centrally heated investments, such as GOAZs, are economically far more profitable than small, scattered greenhouses.

To further validate the Capital Expenditure (CAPEX) predictability, independent regression models were established for infrastructure and superstructure investments against spatial metrics (Figs. 17–18). The models reveal a highly significant correlation between the greenhouse area and infrastructure costs ($R^2 = 0.98$, $p < 0.001$), generating a narrow confidence interval for area-based cost estimations (95% CI: 23.25–27.57). Similarly, superstructure investments yield strong deterministic fits against greenhouse area limits ($R^2 = 0.88$, $p < 0.001$, 95% CI: 10.86–16.84). The robust R^2 values empirically prove that scaling up the physical footprint within a clustered GOAZ systematically distributes initial fixed costs, offering high financial predictability for institutional fund allocations.

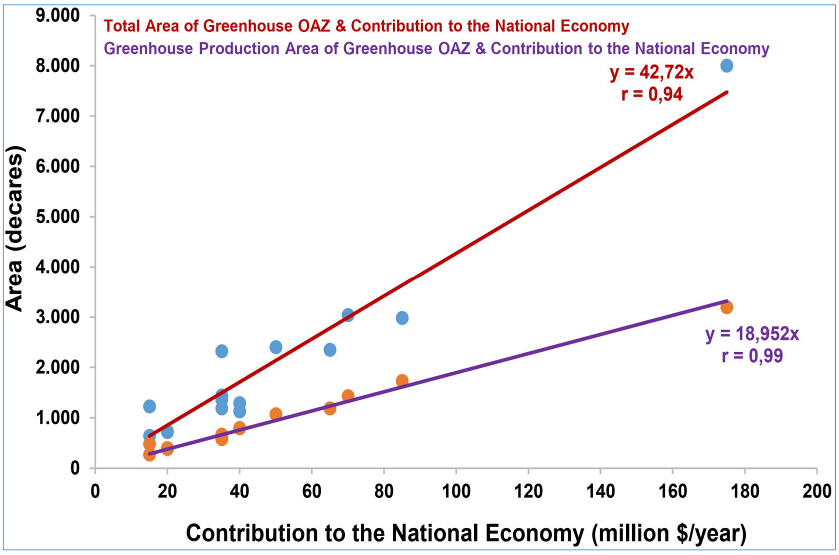

Fig. 20. The relationship between the area of Geothermal GOAZs and their estimated contribution to the national economy (see Table 3)

The economic superiority of large-scale clustering is further substantiated by regression models evaluating investment expenditures. The analysis reveals a robust deterministic relationship between agricultural production capacity and estimated infrastructure investment (Fig. 19; $R^2 = 0.86$, $p < 0.001$). The calculated 95% Confidence Interval for the slope coefficient (95% CI: 0.0007 - 0.0012) confirms the strictly constrained variance in investment costs across different project scales. Consequently, empirical evidence shows that centralizing geothermal infrastructure across clustered greenhouse parcels systematically minimizes per-unit capital expenditure (CAPEX). In small, scattered greenhouse investments, infrastructure and superstructure costs per ton of capacity extend the payback period (IRENA, 2023a; Rezaei et al., 2024). In contrast, centrally planned, organized agricultural zones such as GOAZ transform geothermal agricultural investment into a rational, globally competitive industrial model by distributing high infrastructure and superstructure costs evenly across a wide area.

4.4. Contribution to the National Economy

The integration of geothermal greenhouses into the national economy transcends a mere agricultural growth initiative; it serves as a powerful strategic lever for energy security, rural development, and macroeconomic stabilization. Simultaneously, the uninterrupted 12-month production model suppresses seasonal price fluctuations (agricultural inflation), while the resulting high-yield and premium-quality harvests exponentially boost the country's agricultural export volume and competitiveness. Furthermore, the skilled employment and technology transfer generated by the on-site utilization of geothermal resources accelerate rural development, providing a multifaceted and sustainable value-add to the national economy (Mertoğlu et al., 2020; Lund and Toth, 2021; IRENA, 2023b).

It is observed that GOAZs generate $1 million in annual revenue for the national economy from each 18.95-decacre greenhouse production area, with a total land area of 42.72

decares (Fig. 20). Variations in total land area stem from project-specific spatial differences in infrastructure elements such as administrative buildings, roads, and social amenities. This data demonstrates the highly efficient and strategic role that Turkiye's abundant geothermal resource potential plays in transforming these resources into high-value-added economic contributions through integrated agricultural facilities (GOAZs).

The direct translation of spatial land utilization into macroeconomic value addition is statistically proven through area-to-revenue models (Fig. 20). The regression of the national economic contribution against the greenhouse production area exhibits a near-perfect fit ($R^2 = 0.98$, $p < 0.001$), indicating a tightly constrained multiplier effect (95% CI: 17.35 - 20.55 decares per 1 million USD generated). This exceptional correlation verifies that the GOAZ model optimizes land-use efficiency far beyond fragmented open-field agriculture, delivering a highly bankable framework for sovereign and international economic impact assessments.

While every 654.9 tons of production at Geothermal GOAZs contributes $1 million directly to the national economy (Fig. 21), in small and dispersed geothermal greenhouse operations, this value-added ratio is 30-40% lower due to logistics costs and energy inefficiency (Zhu et al., 2022). In these decentralized, small-scale operations, reduced heating efficiency increases energy consumption per unit area, and the need for each facility to make independent infrastructure investments significantly suppresses the generated unit value added (Rosas-Casals et al., 2022; Shortall et al., 2024). In contrast, GOAZs maximize revenue per ton by enabling the export of products as processed/value-added rather than in bulk, thanks to the integrated facilities they house, such as packaging and cold storage units. The planned clustering model offered by Geothermal GOAZs goes beyond minimizing energy and infrastructure losses; it is a reliable, high-return, innovative investment model fully aligned with macroeconomic goals that directly contributes to reducing the current account deficit by eliminating dependence on imported fossil fuels for heating.

One of the biggest drawbacks of traditional open-field farming is that employment is concentrated during harvest seasons and is both precarious and seasonal. In contrast, fully controlled greenhouses heated by geothermal energy enable year-round, uninterrupted production, thereby shifting the agricultural workforce from a seasonal cycle to continuous employment (IRENA, 2023b; Shortall et al., 2024). In contrast, international socio-economic analyses reveal that the employment structure in small, dispersed geothermal greenhouse operations is of low quality (IRENA, 2023b).

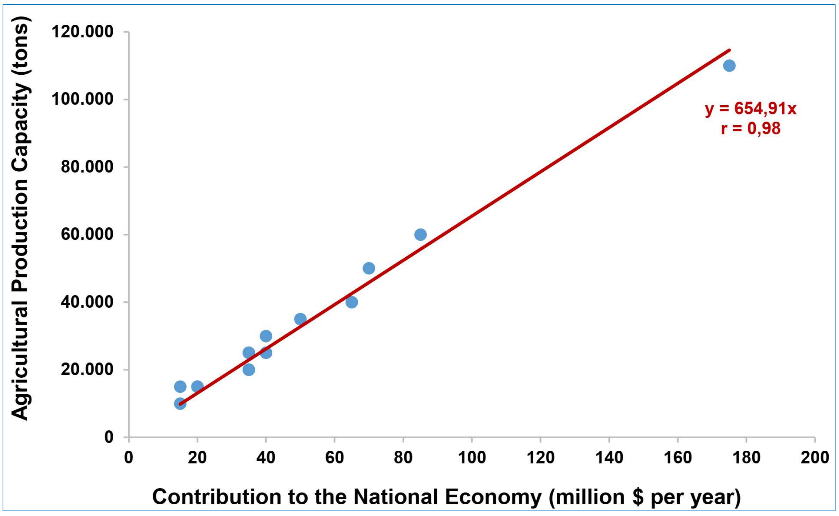

Fig. 21. The relationship between the agricultural production capacity of Geothermal Greenhouse OAZs and their estimated contribution to the national economy (see Table 3)

In dispersed and small-scale operations, the capacity to employ full-time qualified personnel is extremely limited due to the absence of supporting units such as integrated packaging, automation management, and centralized logistics. Since these independent operations lack economies of scale, they are forced to rely heavily on precarious and seasonal labor (Shortall et al., 2024).

A rigorous regression analysis corroborates this macroeconomic multiplier effect. The correlation between agricultural production capacity and the direct national economic contribution (Fig. 21) yields an R^2 of 0.96 ($p < 0.001$), indicating that capacity expansion accounts for the majority of the variance in economic value addition. The calculated confidence intervals indicate that every 1 million USD contributed to the economy corresponds strictly to an increase in production capacity within a defined threshold (95% CI: 575.0 - 734.8 tons). This robust statistical fit renders the Geothermal GOAZ framework a mathematically predictable asset for institutional investors and global policy planners.

4.5. Contribution to Employment

In GOAZs, it is observed that one person is permanently employed for every 0.67 decares of greenhouse production area and every 1.5 decares of total area. Deviations in permanent employment per total area stem from spatial variations caused by project-specific logistical, administrative, and social infrastructure requirements (Fig. 22). In these organized structures, there is a year-round demand for skilled labor not only in basic production stages but also in areas such as climate control, automation, logistics, and packaging. The high capacity for year-round employment per decare offered by GOAZs, across both the greenhouse production sector and the total area, eliminates the fragile labor model found in small-scale greenhouses, providing a multi-layered and secure system that integrates various disciplines, from engineers to packaging workers. The capacity of GOAZ framework to generate continuous rural employment is mathematically tied to its spatial scale (Fig. 22).

The predictive model linking permanent employment to the total operational area presents strong statistical significance (R^2 = 0.84, $p < 0.001$), confirming that structural facility expansion generates predictable job increments (95% CI: 1.11 - 1.88 decares per permanent job). Moreover, the direct dependence of the active greenhouse area on labor requirements strictly governs operational stability. These metrics provide transparent, data-driven validation for ESG-focused investors seeking to maximize socio-economic (S) impacts among rural populations.

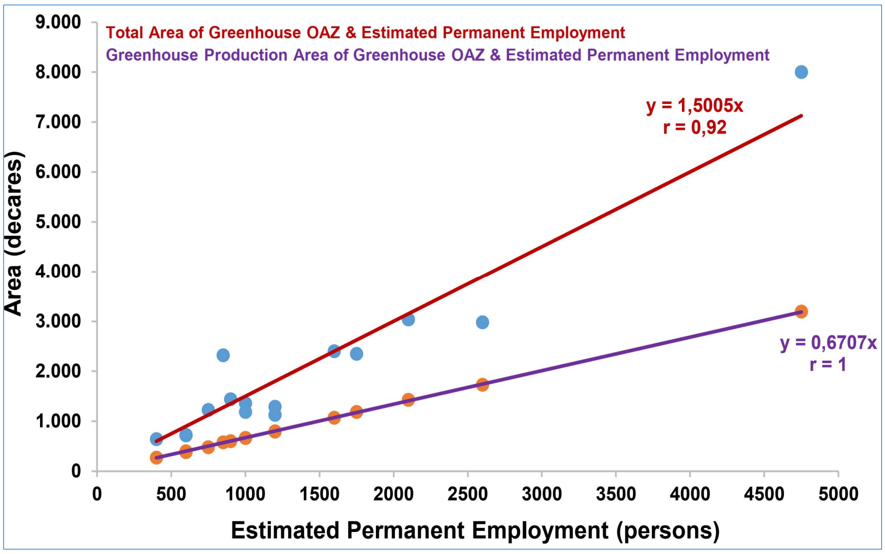

Fig. 22. The relationship between the area of Geothermal GOAZs and estimated permanent employment (see Table 3)

In Geothermal GOAZs, there is one person permanently employed for approximately 23 tons of annual agricultural production capacity (Fig. 23). This indicates that human resource planning for GOAZ investments can be carried out with high precision, reliability, and predictability, aligned with production targets. In small, independent greenhouses, however, labor productivity is declining due to insufficient technological integration and automation (IRENA, 2023a; Shortall et al., 2024), and the employment requirement per unit of tonnage fluctuates, losing its predictability. GOAZs, however, with their continuous employment capacity, eliminate the fluctuating labor model found in small greenhouses; they directly accelerate rural development, prevent rural-to-urban migration, and establish regional prosperity on a sustainable foundation.

The capacity of Geothermal GOAZs to transition agricultural labor into a continuous, high-quality employment model is statistically verified. The regression model linking production capacity to permanent employment (Fig. 23) exhibits an exceptional fit (R^2 = 0.98, $p < 0.001$). The statistical output confirms that a defined production volume is strictly required to sustain continuous rural employment (95% CI: 21.20 - 25.14 tons per person). This demonstrates the high precision and predictability of human resource requirements in clustered models, structurally validating the project's capacity to deliver measurable Social (S) impact within global ESG frameworks

4.6. Macroeconomic Strategies and Economic Dynamics

The financial framework of Geothermal GOAZs not only optimizes infrastructure costs and investment expenditures but also offers strategic advantages to Turkiye within the context of fundamental theories of the global agricultural economy. These integrated zones provide rational solutions to structural issues in the agricultural economy, ranging from foreign trade dynamics in international markets to the creation of regional added value (Fig. 24).

In traditional agriculture, seasonal constraints and time-lags in the production cycle prevent supply from responding simultaneously to price signals, paving the way for sudden fluctuations in consumer prices. This cyclical price volatility, explained by the Cobweb theorem in agricultural economics, continually disrupts market stability because farmers base their production decisions on the previous period's prices (Poitras, 2023; Xie and Wang, 2017).

However, this theoretical bottleneck is eliminated by the Geothermal GOAZ model, which uses low-temperature geothermal fluids to enable uninterrupted production for 12 months. This climate independence in modern greenhouses dampens Cobweb fluctuations arising from supply-demand mismatches, ensuring a stable flow of products to the market (Chaudhry and Miranda, 2018). The stabilization brought about by this continuity of supply minimizes risk in the agricultural value chain, creating the most reliable macroeconomic foundation for long-term, fixed-price contract farming with institutional buyers and international supermarket chains. Additionally, the sustainable management of the geothermal resource (such as reinjection strategies) ensures the long-term (20-30 years) economic viability of the investment.

The relocation of agricultural operations squeezed within urban areas, and the conversion of non-arable lands into productive use are among the core objectives of Geothermal GOAZs. In traditional open-field agriculture, while the economic returns on high-yield lands can be substantial, the associated land investment and operational costs are prohibitively high. The fact that Geothermal GOAZs possess the infrastructure for soilless agriculture (hydroponics) enables projects to be located on marginal, low-cost agricultural lands. This situation minimizes the opportunity cost of investments while accelerating the project's return on investment (ROI) period.

Within the Geothermal GOAZs, a strong network of industrial symbiosis is being established, with a wide range of industries operating from crop production and fresh fruit and vegetable packaging units to frozen food and fruit juice production facilities. This spatial organization ensures that harvested raw materials are processed within an integrated value chain without leaving the region, transforming them into final, value-added products. This structure creates a regional macroeconomic multiplier effect through the employment it generates and the demand it creates for supporting industries, thereby maximizing agricultural gross domestic product.

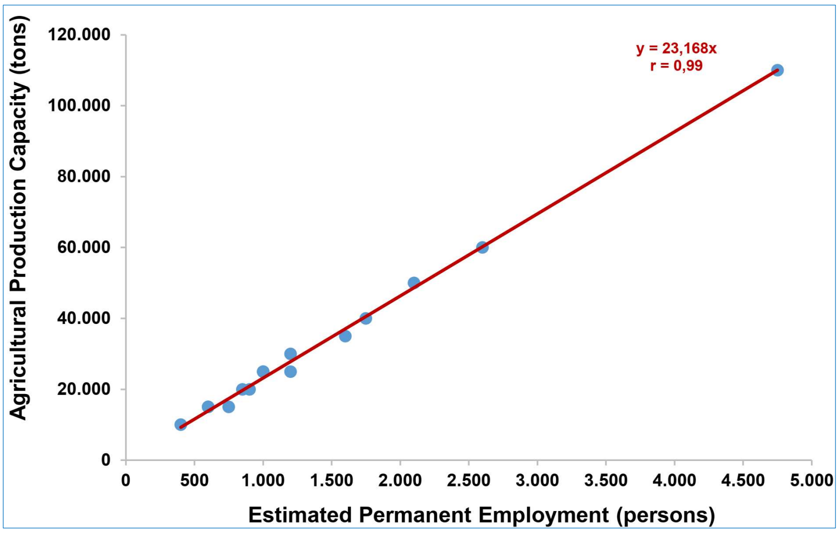

Fig. 23. The relationship between the agricultural production capacity of Geothermal GOAZs and estimated permanent employment (see Table 3)

For high-tonnage production in Geothermal GOAZs to be exported to international markets without barriers and to generate the targeted economic value added, Good Agricultural Practices (GAP) certifications are a strategic necessity. The international agricultural economics literature demonstrates that standards such as GlobalG.A.P. secure product access to export markets and provide a significant 'premium pricing' advantage over standard products (Bui and Nguyen, 2021). Integrated and controlled structures like GOAZs offer a substantial operational advantage over individual, scattered greenhouses in complying with GAP standards, which require traceability, hygiene, and controlled use of chemicals. The centralized management of GAP certification within such planned agricultural clusters both reduces audit costs and enhances operational efficiency, thereby maximizing the return on investment and business profitability (Niyommaneerat et al., 2022).

Consequently, GAP certifications not only guarantee food safety and environmental sustainability but also elevate the facility's financial and commercial performance to global competitive standards by eliminating operational risks (such as chemical residues and hygiene issues) in greenhouse systems (Schreinemachers et al., 2020).

The Carbon Border Adjustment Mechanism (CBAM) implemented by the European Union is reshaping the rules of competition in global trade around the principle of environmental sustainability. This mechanism aims to prevent carbon emissions by imposing additional carbon costs on imported products with high carbon footprints (Böhringer et al., 2022). When evaluated in the context of agricultural exports, products from traditional, small-scale, and dispersed greenhouses heated with fossil fuels such as coal or natural gas will face a significant CBAM tax in the EU market due to their high emissions, thereby reducing their price competitiveness (Zhong and Pei, 2022). In contrast, Geothermal GOAZs integrated with renewable energy sources will be completely exempt from these additional international tax barriers thanks to their zero-emission heating infrastructure. The organized and integrated use of geothermal resources does not limit GOAZ projects to merely being an environmentally friendly model; it also transforms them into a strategic macroeconomic development initiative that secures the country's share in the global market and its foreign exchange earnings by providing the advantage of carbon neutrality in exports (Overland and Sabyrbekov, 2022). The zero-emission production model does more than just facilitate market access. It further strengthens the project's financial viability through an additional revenue stream from the sale of carbon credits in voluntary carbon markets.

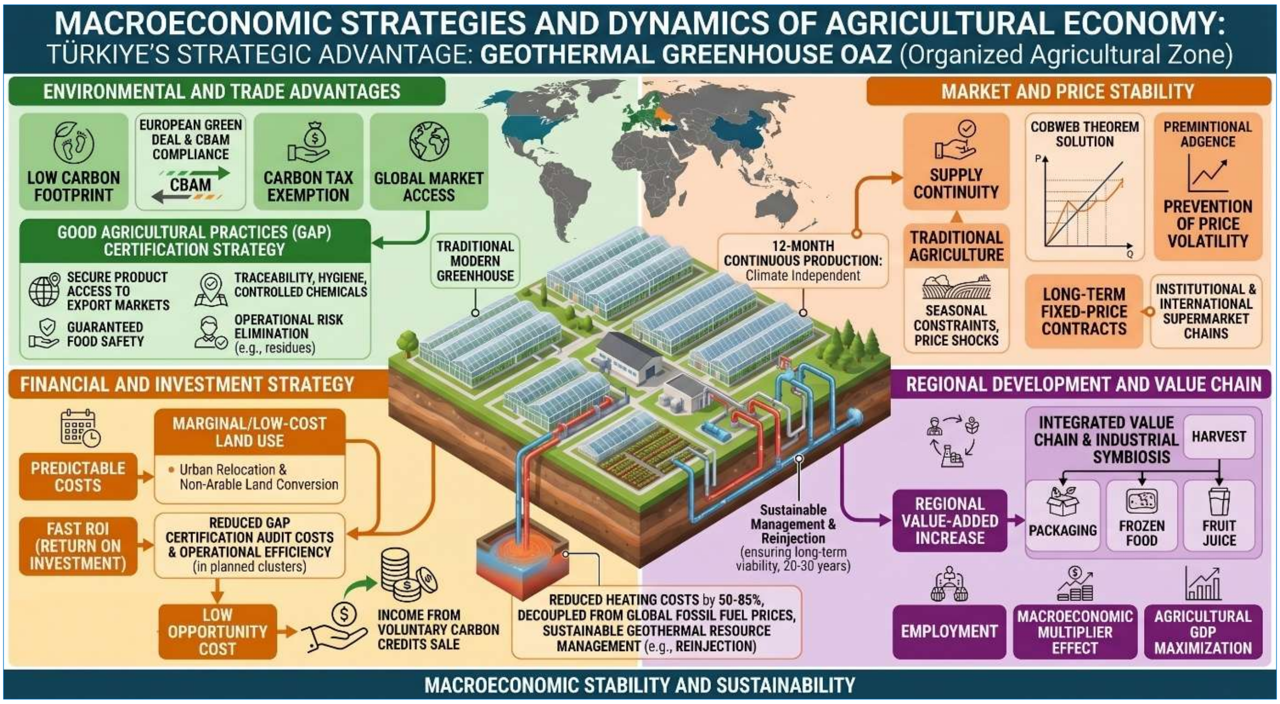

Fig. 24. Macroeconomic strategies and the dynamics of the agricultural economy

5. Conclusion

Ultimately, the GOAZ clustering model provides a rigorously structured, data-driven framework that seamlessly integrates environmental sustainability with high-yield agricultural economics. By centralizing infrastructure and resource management under a sovereign-backed Public-Private Partnership (PPP) governance structure, the model effectively mitigates the high CAPEX and technical risks that typically deter private investment in geothermal agriculture. The statistical validation from Turkiye's mega-scale case study unequivocally demonstrates that spatial clustering yields strict economies of scale, thereby establishing a highly predictable and secure asset class. Moreover, its exceptional ESG performance, highlighted by zero-emission heating, CBAM compliance, and gender-inclusive employment, positions it as an ideal target for global green finance. Beyond Turkiye's specific hydrothermal context, the inherent adaptability of this model, enabled by shallow geothermal heat pumps, ensures its global replicability. The GOAZ framework is not merely a regional policy initiative; it is a scientifically validated, scalable blueprint ready for worldwide implementation to secure resilient food and energy supply chains. As fully bankable, ESG-compliant infrastructure models, GOAZs offer a standardized, turnkey investment vehicle for governments, institutional investors, and global climate funds worldwide.

References

Anifantis, A.S., Pascuzzi, S., Scarascia-Mugnozza, G., 2016. Geothermal source heat pump performance for a greenhouse heating system: an experimental study. Journal of Agricultural Engineering 47 (3), 164-170. https://doi.org/10.4081/jae.2016.544.

Apostolopoulos, N., Goulas, C., Flouros, F., Papadopoulos, G., & Apostolopoulos, S., 2026. The impact of the energy crisis on the food market, the energy transition, and energy poverty after the outbreak of the Russia–Ukraine war: A systematic literature review. Frontiers in Sustainable Energy Policy 3, 1755555. https://doi.org/10.3389/fsuep.2026.1755555.

Argento, S., Garcia, G., Treccarichi, S., 2024. Sustainable and low-input techniques in Mediterranean greenhouse vegetable production. Horticulturae 10 (9), 997. https://doi.org/10.3390/horticulturae10090997.

Ataseven, Y., 2023. Evaluation of the possible effects of the European Green Deal process on agricultural policies in Türkiye. Journal of Agricultural Sciences 29 (1), 13-25. https://doi.org/10.15832/ankutbd.1108754.

Barbier, E. 2002. Geothermal energy technology and current status: an overview. Renewable and Sustainable Energy Reviews, 6(1-2), 3-65. https://doi.org/10.1016/S1364-0321(02)00002-3.

Bas, T.G. 2025. Globalization vs. Glocalization: Learn lessons from two global crises, such as the Russia–Ukraine conflict and the COVID-19 pandemic, for the agro-food and agro-industrial sector. Agriculture 15 (2), 155. https://doi.org/10.3390/agriculture15020155.

Bataineh, K. 2024. Hybrid fuel-assisted solar-powered Stirling engine for combined cooling, heating, and power systems: A review. Energy 300, 131506. https://doi.org/10.1016/j.energy.2024.131506.

Benke, K., Tomkins, B., 2017. Future food-production systems: vertical farming and controlled-environment agriculture.

Sustainability: Science, Practice and Policy 13 (1), 13-26. https://doi.org/10.1080/15487733.2017.1394054.

Bhattarai, K., Ogden, A. B., Pandey, S., Sandoya, G.V., Shi, A., Nankar, A. N., Jayakodi, M., Huo, H., Jiang, T., Tripodi, P., Dardick, C., 2025. Improvement of crop production in controlled environment agriculture through breeding. Frontiers in Plant Science 15, 1524601. https://doi.org/10.3389/fpls.2024.1524601.

Boyacı, S., Kocięcka, J., Jagosz, B., Atılgan, A., 2025. Energy efficiency in greenhouses and comparison of energy sources used for heating. Energies 18(3), 724. https://doi.org/10.3390/en18030724.

Bozoğlu, M., Gündoğdu, H., 2024. The Structural and Regulatory Status of Fragmentation in Agricultural Lands in Turkey. In M. Yağbasan (Ed.), Academic Research and Evaluations in the Social Sciences II, 131-146. https://doi.org/10.58830/ozgur.pub493.c2087.

Böhringer, C., Fischer, C., Rosendahl, K.E., 2022. Cost-effective climate policies and the Carbon Border Adjustment Mechanism. Energy Economics 115, 106365. https://doi.org/10.1016/j.eneco.2022.106365.

Bui, H.T., Nguyen, H.K., 2021. Market access and premium pricing through GlobalGAP certification: A study of modern greenhouse systems. Journal of Cleaner Production 294, 126298. https://doi.org/10.1016/j.jclepro.2021.126298.

Carotti, L., Gori, V., Marrocchio, C., 2023. Hybrid (gas and geothermal) greenhouse simulations aimed at optimizing investment and operative costs: A case study in NW Italy. Energies 16 (9), 3931. https://doi.org/10.3390/en16093931.

Chaudhry, M.I., Miranda, M.J., 2018. Complex price dynamics in vertically linked cobweb markets. Economic Modelling, 72, 363-378. https://doi.org/10.1016/j.ecmode.2018.01.021.

Cowan, N., Ferrier, L., Spears, B.M., Drewer, J., Reay, D.S., Skiba, U., 2022. CEA systems: the means to achieve future food security and environmental sustainability?. Frontiers in Sustainable Food Systems 6, 891256. https://doi.org/10.3389/fsufs.2022.891256.

Çelmen, O., Elidemir, S., Karadağlar, M., 2025. Update on the utilisation of geothermal energy for space and greenhouse heating in Türkiye. Bulletin of the Mineral Research and Exploration 177, 146-157. https://doi.org/10.19111/bulletinofmre.1716476.

MEUCC, 2024. İklim Değişikliği Azaltım Stratejisi ve Eylem Planı (2024-2030) [Climate Change Mitigation Strategy and Action Plan (2024-2030)], Ministry of Environment, Urbanization, and Climate Change of Turkiye. https://iklim.gov.tr/db/turkce/icerikler/files/İklim_Değişikliği_Azaltım_Stratejisi_ve_Eylem_Planı_(2024-2030).pdf.

Dikili Geothermal GOAZ, 2025. Faaliyet Raporu (2024-2025) [Activity Report (2024-2025)]. https://www.dikilitdiosb.org.tr/wp-content/uploads/DIKILI_OTB_FAALIYET-RAPORU-26.12.2025.pdf.

Dimitropoulou, A.-M.N., Giannini, E.N., Maroulis, Z.B. 2025. A greenhouse profitability model: The effect of the energy system. Energies 18 (17), 4748. https://doi.org/10.3390/en18174748.

DiPippo, R., 2012. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact (3rd Edition). Butterworth-Heinemann, 624 p.

Dsouza, A., Newman, L., Graham, T., Fraser, E.D.G., 2023. Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics. Agricultural Systems 209, 103673. https://doi.org/10.1016/j.agsy.2023.103673.

Du, M., Chen, Y., Liu, S., Xiao, L., 2026. From segmentation to linkage: The spatial effect of technological structure change on driving high-quality agricultural development in Xinjiang. Frontiers in Sustainable Food Systems 10, 1781650. https://doi.org/10.3389/fsufs.2026.1781650.

EGEC, 2022. EGEC Geothermal Market Report: Shallow geothermal energy sector and regulatory frameworks. European Geothermal Energy Council, https://www.egec.org/media-publications/egec-geothermal-market-report-2022/.

Elshehabi, T., Alfehaid, M., 2025. Sustainable geothermal energy: A review of challenges and opportunities in deep wells and shallow heat pumps for transitioning professionals. Energies 18 (4), 811. https://doi.org/10.3390/en18040811.

Esenlikci, A.C., 2023. Türkiye'de organize sanayi bölgelerinin yeşil dönüşümü: Yeşil organize sanayi bölgesi projesi [Green transformation of organized industrial zones in Turkey: Green organized industrial zone project]. Nevşehir Hacı Bektaş Veli Üniversitesi SBE Dergisi 13 (1), 337-357. https://doi.org/10.30783/nevsosbilen.1212711.

Fiankor, D.D.D., Flachsbarth, I., Masood, A., Brümmer, B., 2020. Does GlobalGAP certification promote agrifood exports? European Review of Agricultural Economics 47 (1), 247-272. https://doi.org/10.1093/erae/jbz023.

Filimonau, V., Hattingh, L., Neave, S., Parfitt, C., 2024. The opportunities and challenges of provisioning low pesticide risk fresh produce by smallholder farmers to hospitality and foodservice organizations. Journal of Foodservice Business Research. https://doi.org/10.1080/15378020.2024.2372483.

GeoPLASMA-CE, 2019. Strategies for the planning, mapping, and management of shallow geothermal energy in Central Europe. Interreg Central Europe Program. https://programme2014-20.interreg-central.eu/Content.Node/GeoPLASMA-CE.html.

Githiga, J., Elias, A., Yasunobu, K., 2024. The effect of GlobalGAP certification on horticulture production in Kenya. International Journal of Environmental and Rural Development 15 (1), 8-15. https://www.jstage.jst.go.jp/article/ijerd/15/1/15_8/_article.

Glassley, W.E., 2014. Geothermal Energy: Renewable Energy and the Environment (2nd Edition). CRC Press, 424 p.

Gomez, C., Currey, C.J., Dickson, R.W., Kim, H.J., Hernandez, R., Sabeh, N.C., Raudales, R.E., Brumfield, R.G., Laury-Shaw, A., Wilke, A.K., Lopez, R.G., Burnett, S.E., 2019. Controlled environment food production for urban agriculture. HortScience 54 (9), 1448-1458. https://doi.org/10.21273/HORTSCI14073-19.

Guarino, S., Catrini, P., Buscemi, A., Lo Brano, V., Piacentino, A., 2021. Assessing the energy-saving potential of a dish-Stirling concentrator integrated into energy plants in the tertiary sector. Energies 14 (4), 1163. https://doi.org/10.3390/en14041163.

Guiné, R.P.F., 2024. The challenges and strategies of food security under global change. Foods, 13(13), 2083. https://doi.org/10.3390/foods13132083.

Gürpınar, K., Aktürk, A., 2023. Evaluation of the Competitive Advantage of Afyonkarahisar Province Sandıklı District Geothermal Greenhouse Sector in the Light of Executive Opinions. Journal of Strategic Management Research 6 (2), 163-184. https://doi.org/10.54993/syad.1336595.

Haehnlein, S., Bayer, P., Blum, P., 2010. International legal status of the use of shallow geothermal energy. Renewable and Sustainable Energy Reviews 14 (9), 2611-2625. https://doi.org/10.1016/j.rser.2010.07.069.

Hamam, M., Spina, D., Raimondo, M., Di Vita, G.D., Zanchini, R., Chinnici, G., Tóth, J.R., D'Amico, M., 2023. Industrial symbiosis and agri-food system: Themes, links, and relationships. Frontiers in Sustainable Food Systems 6, 1012436. https://doi.org/10.3389/fsufs.2022.1012436.

Hao, S., Liu, L., Wang, G., 2025. Spatio-temporal evolution and driving factors of China's agro-processing industry. Frontiers in Sustainable Food Systems, 9, 1685935. https://doi.org/10.3389/fsufs.2025.1685935.

IKA and UNDP, 2022. IKA (Izmir Development Agency of Turkiye) & UNDP (United Nations Development Program) Endüstriyel simbiyoz: [Industrial Symbiosis]. https://endustriyelsimbiyoz.ikvp.izka.org.tr/.

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/

IRENA, 2023a. Global geothermal market and technology assessment. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/Publications/2023/Feb/Global-geothermal-market-and-technology-assessment.

IRENA, 2023b. Socio-economic footprint of the energy transition: Geothermal energy and rural employment. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Socioeconomic-footprint_energy_transition_SE_Asia_2023.pdf.

Işık, S.E., Adedoyin, F.F., Bekun, F.V., 2023. Impact of the European Green Deal (EGD) on the agricultural carbon (CO_2) emission in Turkey. International Journal of Sustainable Development and Planning 18 (3), 859-866. https://doi.org/10.18280/ijsdp.180307.

Jung, Y., Kim, J., Kim, H., Yun, R., Park, C., Nam, Y., Cho, H., Lee, H., 2021. Comprehensive feasibility investigation of river source heat pump systems in terms of life cycle. Applied Thermal Engineering 188, 116655. https://doi.org/10.1016/j.applthermaleng.2021.116655.

Kapur, B., Solmaz, D., Kekeç, U., Erkan Can, M.E., 2024. The development of greenhouses in the southern Türkiye, with an emphasis on their structural and agricultural features: The case of the Mersin province. Çukurova Journal of Agricultural and Food Sciences 39 (1), 68-81. https://doi.org/10.36846/CJAFS.2024.134.

Karagöl, V., 2025. Global food prices in the shadow of uncertainties, risks and volatilities. International Journal of Economics 40 (4), 1001-1019. https://doi.org/10.24988/ije.1554013.

Karytsas, S., Mendrinos, D., Radoglou-Grammatikis, P., 2022. Examining the development of a geothermal risk mitigation scheme in Greece. Clean Technologies 4 (2), 346-364. https://doi.org/10.3390/cleantechnol4020021

Kındap, A., 2023. Tarımda jeotermal devri [The geothermal revolution in agriculture]. Geothermal Energy Association of Turkiye. https://jeotermalenerjidernegi.org.tr/public/pdf/99840590.pdf.

Kurpaska, S., Janowski, M., Gliniak, M., Krakowiak-Bal, A., Ziemiańczyk, U., 2021. The use of geothermal energy to heating crops under cover: A case study of Poland. Energies 14 (9), 2618. https://doi.org/10.3390/en14092618.

Laili, N., Djatna, T., Indrasti, N., Yani, M., 2024. Optimization of industrial symbiosis in coffee-based eco-industrial park design. Global Journal of Environmental Science and Management 10 (2), 621-642. https://doi.org/10.22034/gjesm.2024.02.13.

Lee, C., Kang, G.C., Jang, J.K., Yun, S.-W., Moon, J.P., Mun, H.-S., Lagua, E.B., 2020. Numerical simulations on the application of a closed-loop lake water heat pump system in the Lake Soyang, Korea. Energies 13 (3), 762. https://doi.org/10.3390/en13030762.

Lee, C.G., Kang, G.C., Jang, J.K., Yun, S.-W., Moon, J.P., Mun, H.-S., Lagua, E.B., 2025. Efficacy of hybrid photovoltaic–thermal and geothermal heat pump system for greenhouse climate control. Energies 18 (20), 5386. https://doi.org/10.3390/en18205386.

Liew, Y.S., Tan, L.K., Chua, S.C., 2021. Seawater as renewable energy in air conditioning and plumbing systems for coastal development. International Journal for Innovation Education and Research 9 (9), 540-555. https://doi.org/10.31686/ijier.vol9.iss9.3361.

Li, X., Wei, J., Chen, H., 2025. Exploring the driving mechanisms behind the formation of agricultural science and technology innovation clusters. Frontiers in Sustainable Food Systems 9, 1607580. https://doi.org/10.3389/fsufs.2025.1607580.

Lu, H., Li, Q., Liu, B., Chi, Z., Ye, Y., 2023. Research on the dynamic changes of China's agro-processing industry agglomeration and spatial impact of production factors on agglomeration. PLOS ONE 18 (12), e0292870. https://doi.org/10.1371/journal.pone.0292870.

Lund, J.W., Toth, A.N., 2021. Direct utilization of geothermal energy 2020 worldwide review. Geothermics 90, 101915. https://doi.org/10.1016/j.geothermics.2020.101915.

Mertoğlu, O., Şimşek, Ş., Başarır, N., 2020. Geothermal Energy Use - Projections, Country Update for Turkey. Proceedings World Geothermal Congress, Reykjavik, Iceland.https://www.researchgate.net/publication/352478313_Geothermal_Energy_Use_Projections_and_Country_Update_for_Turkey.

Ngirubiu, I.I., Batlles-delaFuente, A., Franco-García, M.-L., 2026. Circular Economy in Agri-food Greenhouses: Lessons from the Netherlands. In Evidence and Action on the UNSDGs: Reviews and Case Studies. Emerald Publishing Limited. https://doi.org/10.1108/978-1-83662-602-220261005.

Niyommaneerat, W., Maclean, M., Salam, P.A., 2022. Adoption of Good Agricultural Practices (GAP) and its impact on financial performance: Evidence from farming clusters. Land Use Policy 119, 106197. https://doi.org/10.1016/j.landusepol.2022.106197.

Overland, I., Sabyrbekov, A., 2022. Know your enemy: How the carbon border adjustment mechanism works and why it matters. Energy Research & Social Science 92, 102809. https://doi.org/10.1016/j.erss.2022.102809.

Özel, E., Esmer, Y., 2024. Social and economic problems of agricultural enterprises: The case of Bayburt. Turkish Journal of Agricultural and Natural Sciences 11 (4), 890-903. https://doi.org/10.30910/turkjans.1445211.

Özkan, M., 2024. We aim to expand geothermal greenhouse farming to 100,000 acres. We rank fourth in the world and second in Europe in terms of greenhouse capacity. Turkish Journal of Agriculture and Forestry. Ministry of Agriculture and Forestry of Turkiye. https://www.turktarim.gov.tr/Haber/1104/jeotermal-seraciligi-100-bin-donume-cikarmayi-hedefliyoruz.

Pająk, L., Tomaszewska, B., Bujakowski, W., 2024. Assessment of potential heat resources in stratified lakes in Poland in the era of the search for clean energy sources. Resources 13 (2), 27. https://doi.org/10.3390/resources13020027.

Poitras, G., 2023. Cobweb Theory, market stability, and price expectations. Journal of the History of Economic Thought 45 (1), 137-161. https://doi.org/10.1017/S105383722200028X.

Porter, M.E. ,1990. The Competitive Advantage of Nations. The Free Press. 352 p.

Ptak, M., Amnuaylojaroen, T., Sojka, M., 2025. Heat resources of rivers in the Odra River Basin as a potential element implement for sustainable development in Poland. Resources 14 (12), 184. https://doi.org/10.3390/resources14120184.

Rezaei, F., Burg, V., Pfister, S., Hellweg, S., Roshandel, R., 2024. Spatial optimization of industrial symbiosis for heat supply of agricultural greenhouses. Journal of Industrial Ecology 28 (1), 1-15. https://doi.org/10.1111/jiec.13543.

Rosas-Casals, M., Gamarra, A. R., Smaniotto, C., 2022. Sustainability and economic viability of decentralized geothermal systems for agriculture in rural areas. Journal of Cleaner Production 358, 132045. https://doi.org/10.1016/j.jclepro.2022.132045.

Schreinemachers, P., Grovermann, C., Praneetvatakul, S., Heng, P., Nguyen, T.T., Buntong, B., Le, N.T., Pinn, T., 2020. Safe and sustainable agriculture: The impact of Good Agricultural Practices certification on pesticide use and farm income. Ecological Economics 176, 106733. https://doi.org/10.1016/j.ecolecon.2020.106733.

Semerci, A., 2021. Tarım işletmelerinde tarımsal kredi kullanım durumunun analizi [Analysis of agricultural credit usage in agricultural enterprises]. Turkish Journal of Agricultural and Natural Sciences 8 (2), 396-410. https://doi.org/10.30910/turkjans.860909.

Seo, J., Seo, U-J., 2021. Ground source heat pump (GSHP) systems for horticulture greenhouses adjacent to highway interchanges: A case study in South Korea. Renewable and Sustainable Energy Reviews 135, 110194. https://doi.org/10.1016/j.rser.2020.110194.

Shortall, R., Bakhtiari, F., Hashemi, M., 2024. Socio-economic impacts of geothermal direct use in agriculture: Job creation and sustainable rural development. Renewable and Sustainable Energy Reviews 189, 113940. https://doi.org/10.1016/j.rser.2023.113940.

Şener, M.F., Uzelli, T., Akkuş, İ., Mertoğlu, O., Baba, A., 2023. The potential, utilization, and development of geothermal energy in Türkiye. Bulletin of the Mineral Research and Exploration 171, 69-90. https://doi.org/10.19111/bulletinofmre.1229381.

Şirikçi, B.S., Çetinkaya, G., 2025. Economic structure of tomato production in geothermal energy-heated greenhouses: Simav district case of Kütahya province. Turkish Journal of Agricultural and Natural Sciences 12 (4), 1139-1152. https://doi.org/10.30910/turkjans.1759246.

Trabert, U., Jesper, M., Bergstraesser, W., Best, I., Kusyy, O., Orozaliev, J., Vajen, K., 2021. Techno-economic evaluation of electricity price-driven heat production of a river water heat pump in a German district heating system. International Journal of Sustainable Energy Planning and Management 31, 121–142. https://doi.org/10.5278/ijsepm.6291.

TDİOSB, 2017. Regulation on the Implementation of Agriculture-Based Specialized Organized Industrial Zones. Official Gazette of the Republic of Turkey, No. 30250. https://www.mevzuat.gov.tr/mevzuat?MevzuatNo=24116&MevzuatTur=7&MevzuatTertip=5.

TRGM, 2024. Investor Guide to Organized Agricultural Zones. General Directorate of Agricultural Reform of Turkiye. https://www.tarimorman.gov.tr/TRGM/Belgeler/YATIRIMCI%20REHBERI%CC%87%202024.pdf.

TTB, 2020-2025. Activity Reports for 2000-2025. (Ministry of Agriculture of Turkiye). https://www.tarimorman.gov.tr/Konular/Plan-Program-Ve-Faaliyet-Raporlari/faaliyet-raporlar%c4%b1.

Ulusoy, K., Doğan-Sağlamtimur, N., Çiner, F., Sternik, A., Sekula, P., 2024. Industrial symbiosis practices: A case study of Türkiye and Denmark. Environmental Research and Technology 8 (1), 224-233. https://doi.org/10.35208/ert.1271679.

Xie, H., Wang, B., 2017. An empirical analysis of the impact of agricultural product price fluctuations on China's grain yield. Sustainability 9 (6), 906. https://doi.org/10.3390/su9060906.

Xu, S., Zhang, Y., 2023. Impact of manufacturing agglomeration on the green innovation efficiency-Spatial effect based on China's provincial panel data. International Journal of Environmental Research and Public Health 20 (5), 4238. https://doi.org/10.3390/ijerph20054238.

Ye, W., Wang, Y., Li, Z., Li, X., 2023. The impact of food production comparative advantage on green total factor productivity: The moderating role of environmental regulation. Agriculture 13 (11), 2058. https://doi.org/10.3390/agriculture13112058.

Zheng, Q., Wen, X., Xiu, X., Yang, X., Chen, Q., 2022. Can the part replace the whole? A choice experiment on organic and pesticide-free labels. Foods 11 (17), 2564. https://doi.org/10.3390/foods11172564.

Zhong, J., Pei, J., 2022. Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's carbon border adjustment mechanism. Energy Policy 162, 112802. https://doi.org/10.1016/j.enpol.2022.112802.

Zhou, B., Zhang, R., Zhang, Z., Li, K., Wang, J., Chen, J., Papadakis, G., Guo, B., 2026. Smart energy supply for smart farms: A hybrid ground source heat pump in seasonal greenhouses for growing cherries. Smart Agricultural Technology 13, 101709. https://doi.org/10.1016/j.atech.2025.101709.

Zhu, J., Bai, H., Wang, Y., 2022. Technical and economic evaluation of decentralized vs. centralized geothermal heating for industrial-scale greenhouse clusters. Energy Reports 8, 1245-1258. https://doi.org/10.1016/j.egyr.2021.12.035.