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Waste-Based Vertical Planting System Proposal to Increase Productivity in Sustainable Horticulture; "PETREE"

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Abstract: The problems experienced with the decrease in agricultural areas per capita against the uncontrolled population growth in the World and in Turkey are becoming increasingly evident. Especially the manpower engaged in horticulture is increasingly experiencing the problems of migration, economic reasons, and inefficient production methods. For healthy and efficient production, agricultural lands need a sequential cycle that includes cultivation and fallow periods. Agricultural lands, the salt they contain, etc. When left fallow, the soil area needs to rest to re-establish the mineral balance. It is now vital for small producers, whose production areas are gradually shrinking due to global conditions, to continue production while their lands are resting to produce more continuously and efficiently. In the face of increasing demands, decreasing production amounts and areas, the constantly increasing prices of economically simple agricultural products "fresh vegetables" and affecting the easy accessibility of local products, it has become inevitable to seek new and alternative solutions. This study includes an innovative solution proposal to increase the production efficiency of low-scale producers and individual gardeners, especially those producing in small agricultural areas. Critical problems of large-scale greenhouse systems, interactions of agricultural practices within the framework of urban life, water and energy efficiency in agriculture, and sustainability and waste management of the proposed system are examined. To meet changing conditions and maintain productivity in small areas, it is envisaged that mobile and vertical production stations, which can produce by increasing productivity even in fallow areas while the soil is resting, can be an alternative solution to the problems of small producers. The vertical planting system "PETREE" develops mobile units for sustainable agriculture by collecting 5th LT-PET packages, which have a natural lifespan of about 90 years, and reusing them as plant pots and some recycled plastic pieces as structures. With efficient and environmentally friendly design suggestions, the system also examined the possibilities of more efficient gardening with mobile production stations in small agricultural areas, and efficient and enjoyable gardening that suits the needs of urban consumers "production with local seeds and seedlings" with the increase in environmental awareness and food safety concerns.

Keywords: mobile gardening; productivity; reuse; recycling; design; environmental awareness

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1. Introduction

As the world undergoes exploitation and depletion, resources diminish as the global population grows, leading to the inevitable rise of severe crises. Furthermore, the agricultural expanse and per capita production are steadily declining. The FAO reports that the global growth rate of agricultural production has slowed down in recent decades, while the global population continues to grow [1]. Despite extensive collaboration and the presence of international organizations, it appears that countries are still far from attaining global water and soil efficiency, as well as cooperative efforts to address food security and biodiversity. The existence of these gaps can be related to a variety of factors, such as divergent political ideologies, economic inequalities, and conflicting interests. The carbon footprint has brought attention to the importance of local production and the "not global but local" mantra. Consequently, small-scale producers and the challenges they face have become prominent in the realm of food production. This puts pressure on food security, particularly in developing countries. The World Bank estimates that food production needs to increase by 70% to meet the demands of a growing global population by 2050 [2].

Improving the productivity of small-scale local farmers, particularly in undeveloped regions should be a key priority for global development. Targeting the productivity of small-scale farmers is critical to reducing poverty and hunger. Strengthening the productivity of local farmers reduces dependence on imported food, enhancing local food security and resilience against external shocks like disruptions in global supply chains [3]. It is critical to emphasize greater and better investment in agricultural technology, infrastructure, and market possibilities for underprivileged farmers [4]. As the world population continues to grow, the natural demand for food and agricultural products must also increase rapidly. The fact that agricultural land per capita is decreasing due to population growth in the world becomes a difficult issue with important consequences for the future in terms of food security and sustainability. However, the hyper-expansion of large cities leads unstoppably to the centralization of urban areas and the conversion of agricultural lands for other purposes [5,6]. These facts inevitably cause worldwide problems for small-scale producers who still rely on agriculture production as their primary source of income. Despite facing numerous challenges, small-scale farms contribute up to 80% of the food consumed in some regions like Sub-Saharan Africa and Asia. Supporting their productivity is crucial for ensuring regional and global food security [7]. Even today, major industrialized countries continue to economically support their local backbone producers and farmers. While majority of producers must still face many difficulties, at different scales, all global problems threaten their livelihoods and cause the problem of decreasing farmland per capita.

This study explores the challenges faced by small producers after the introduction of greenhouse cultivation in next section. The development of greenhouse cultivation, as well as a comparison of problems between horizontal and vertical planting systems, are discussed in the Section 2. The relationships and comparisons between sustainability, waste management, and greenhouse systems are examined in Section 3. The PETREE system is the focus of discussion in the following Section 4. The design principles of the system, its configuration, comparison with vertical planting systems (VPS), and its potential advantages and disadvantages for developing countries like Turkey are thoroughly analyzed.

1.1. Global Problems of Small-Scale Producers

The relocation of rural residents leads to the collapse of small-scale agriculture and exacerbates the decreasing agricultural land per capita. Migration is another major issue in underdeveloped countries compared to the developed ones. It is also a critical reality of small-scale producers in rural areas, where their limited resources and opportunities push individuals to seek better living conditions in urban areas. Economic factors such as low profitability and limited access to capital and markets also provide substantial hurdles for small manufacturers. Limited financial resources frequently prevent them from implementing contemporary farming practices and technologies, hence reducing production and efficiency [8]. Inefficient production procedures are another significant difficulty for small producers. Many of these farmers continue to use conventional farming practices that are labor-intensive and produce low yields.

The lack of knowledge and resources to employ new and sustainable farming techniques adds to the inefficiency of their operations. The primary challenges faced by small-scale producers are outlined in the following order:

1.1.1. Land Scarcity and Loss

- *Rising and expanding urbanization* is one of the biggest threats to small-scale producers on a worldwide scale. Industrial growth and rising commercial land grabbing compete with local and small-scale agriculture, forcing farmers to lose land all over the world [4]. The impact of urbanization on small-scale producers is a well-documented issue,

especially in regions where industrial growth and urban expansion have led to the displacement of local farmers and loss of agricultural land [1].
- *Land degradation* as well as water and soil management issues, disproportionately affected smallholders and their limited resources. Land degradation encompasses desertification, soil erosion, and salinization, all of which degrade and impair agriculture quality and productivity, particularly in developing countries [9].

1.1.2. Economic Challenges

- *Limited Access to Credit and Investment Problems:* Almost all small-scale producers continue to struggle to access loans and investments necessary to upgrade to new technology, infrastructure, and sustainable practices, reducing productivity and competitiveness [10]. Access to credit and investment is a major challenge for small-scale producers around the world. The World Bank reports that 65% of micro, small, and medium enterprises (MSMEs) in developing countries have unmet financing needs [11]. This translates to a financing gap of USD 1.5 trillion globally. The International Labor Organization (ILO): The ILO estimates that 90% of formal businesses globally are MSMEs, and they provide employment for more than half of the global workforce [6]. Limited access to finance can hinder the growth and job creation potential of these businesses. The FAO highlights those small-scale farmers, who play a crucial role in global food security, are particularly constrained by limited access to credit [1,6]. This can limit their ability to invest in productivity-enhancing technologies, such as irrigation systems and improved seeds. Market Volatility and Instability small farmers and producers, particularly in underdeveloped regions and countries, are frequently subjected to fluctuating market conditions and price politics in which they lack bargaining power, leaving them vulnerable to exploitation by middlemen and price drops, which have a vulnerable impact on their income and resilience [12].
- *Resource Constraints:* Small-scale horticultural producers frequently have limitations in accessing crucial resources, including land, water, seeds, fertilizers, financing, and technology. The limited availability of resources substantially impacts their ability to produce and generate profit. For instance, a study conducted in Kenya [13] revealed that small-scale horticultural farmers needed help in obtaining high-quality seeds and fertilizers, which restricted their crop productivity. Small-scale horticultural producers in Turkey also frequently face challenges because of their limited access to resources, which hinders their production and their capacity to compete in the market [13].
- *Market Constraints:* Global markets often present challenges for small-scale horticulture producers in terms of competition, price volatility, and access to markets. A study in Chile [14] revealed that small-scale fruit producers faced difficulties in accessing export markets due to stringent quality standards and competition from larger producers. Similarly, small-scale horticulture producers in Turkey face market challenges such as price volatility, competition from larger producers, and difficulty in accessing export markets. These constraints affect their profitability and market penetration [15].

1.1.3. Social Problems

- *The fragmentation of land* due to inheritance contributes to global issues such as poverty, limited opportunities, and climate change, prompting individuals to relocate to urban areas at a young age. This inevitable migration causes less developed countries to experience a slowdown in the productivity and intellectual capacity of the agricultural labor force, which has been present in rural communities for millennia [12].
- *The aging population and loss of agriculture power* are also a rising problem in underdeveloped regions when the "youth leave" workforce ages, small-scale farmers and producers confront significant barriers to the adoption of new technology and innovations that are critical for adjusting to changing conditions [16].

- *Social factors* such as gender inequities, lack of education, and limited access to extension services can further marginalize small-scale horticulture producers. A study in Tanzania [17] highlighted how female farmers faced challenges in accessing agricultural training and resources, impacting their production capabilities. Social factors, including gender disparities, limited access to education and extension services, and land ownership issues, also contribute to the challenges faced by small-scale horticulture producers in Turkey. Women farmers may face additional barriers in accessing resources and support for their agricultural activities [8].

1.1.4. Additional Challenges

- *Global Climate Change* is still a major problem for all, in which increasingly variable weather and season conditions, water scarcity, earthquakes, droughts, and over-flooding have threatened and skewed overall agricultural production and small-producer stability in income [15]. Small-scale horticulture producers are vulnerable to the adverse effects of climate change, including unpredictable weather patterns, droughts, floods, and pest outbreaks. Research in Vietnam demonstrated how climate variability has impacted small-scale vegetable producers, leading to crop losses and reduced incomes [18].
- *Lack of Infrastructure and Support Services:* The quality of infrastructure always affects the quality of life, particularly in developing countries. Limited access to infrastructure, including roads, storage facilities, extension services, and communication technology, might restrict market access, information sharing, and optimal practices implementation. The absence of proper infrastructure, including storage facilities, transportation networks, and market linkages, hinders the efficiency of small-scale horticulture production. In India, small-scale vegetable producers struggle with post-harvest losses due to inadequate cold storage facilities, as highlighted in a report by ICRISAT [19]. The inadequate infrastructure, including storage facilities, transportation networks, and market linkage systems, poses significant challenges for small-scale horticulture producers in Turkey. The lack of proper infrastructure leads to post-harvest losses and limits market access for producers [15].
- *Land ownership problems* persist in most impoverished countries. Small-scale producers and farmers continue to experience insecure land tenure rights, which have a significant impact on long-term planning and sustainable land management practices by smallholders. This problem persists in most impoverished countries. Small-scale producers and farmers continue to experience insecure land tenure rights, which significantly hinders long-term investment and adoption of sustainable land management practices by smallholders [20,21].

In conclusion, addressing the major global problems of small-scale horticulture producers requires a multifaceted approach that considers the contextual challenges faced by farmers in different countries. By providing targeted support in terms of resources, infrastructure development, market access, climate resilience, and social inclusion, policymakers and stakeholders can enhance the resilience and livelihoods of small-scale horticulture producers worldwide. By addressing these major global problems and providing targeted support in terms of resource access, infrastructure development, market opportunities, climate resilience, and social empowerment, policymakers and stakeholders in Turkey can enhance the livelihoods and sustainability of small-scale horticulture producers in the country [15].

1.1.5. Possibilities for the Future

Maybe it is a good time to focus on more effective and target-oriented micro solutions that could be a start for producers struggling to survive in rural areas. Focusing on more effective and targeted micro solutions could serve as a promising approach for small-scale producers facing challenges in rural areas. The concept involves the creation of mobile and vertical production stations that are adaptable to evolving global conditions, sustaining productivity in limited spaces, and enhancing yield in fallow areas during soil rejuvenation periods. Moreover, the development of solutions enabling agricultural production through vertical stations in non-arable regions could open new opportunities for cultivation. Addressing these innovative agricultural practices, a novel vertical planting system known as the "PETREE" system has emerged as a potential alternative solution for small-scale producers. This study explores the economic viability of the PETREE proposal, presenting a vertical planting system design aimed at maximizing the efficient utilization of small agricultural spaces through environmentally sustainable measures. By implementing the PETREE system and its design recommendations, small-scale producers may enhance productivity, optimize resource utilization, and foster environmentally friendly agricultural practices in compact agricultural areas, ultimately contributing to the resilience and sustainability of rural farming communities.

2. Exploring the Greenhouse Technology

In academic terminology, greenhouse technologies are artificial controlled habitats created to develop plants. These settings regulate temperature, humidity, light, and other environmental parameters to maximize growth and productivity. The plants can be placed both horizontally and vertically within these systems [22]. Greenhouses also provide a protected and controlled environment for plants, allowing for year-round cultivation and increased productivity compared to traditional open-field farming methods without affecting the season periods. Academic definitions of greenhouse systems often emphasize their role in sustainable agriculture, resource efficiency, and climate resilience [23,24]. Nowadays, greenhouse systems play a crucial role in industrial food production by providing controlled environments for cultivating crops and maximizing productivity. Greenhouses offer a range of benefits, including enhanced crop quality, year-round production, protection from pests and diseases, and efficient resource utilization. In the context of industrial food production, greenhouse systems contribute to ensuring food security, reducing the reliance on unpredictable weather conditions, and meeting the increasing demand for fresh produce sustainably. That is the reason why small-scale producers need efficient, effective, and economic industrial greenhouse systems and solutions all around the world [21,23].

After the Industrial Revolution, greenhouse technology and systems evolved significantly to meet the growing demands of industrial food production. The developments in greenhouse technology post-Industrial Revolution include the following:

1. Advancements in materials: The introduction of new materials such as glass, polycarbonate, and plastics revolutionized greenhouse construction, allowing for better insulation, light transmission, and durability.
2. Automation and control systems: The integration of automation, sensors, and control systems enabled precise monitoring and adjustment of environmental conditions within greenhouses, optimizing plant growth and resource use efficiency.
3. Sustainable practices: The emphasis on sustainability led to the adoption of energy-efficient technologies, water-saving irrigation systems, and integrated pest management strategies in greenhouse production.
4. Vertical planting and hydroponics: Innovations in vertical planting and hydroponic systems expanded the capacity for crop production in limited spaces, increasing productivity and resource efficiency.
5. Climate resilience: Greenhouse systems have been developed to withstand climate variability and extreme weather events, ensuring a stable and reliable food supply throughout the year.

Greenhouse systems have become essential in industrial food production due to their capacity to establish a controlled environment for cultivating crops. This leads to improved efficiency, quality, and sustainability in food production. The Industrial Revolution spurred the progress of greenhouse technology, resulting in advancements in materials, automation, sustainable practices, vertical planting, and climate resistance. The advancements have enhanced the capacity and effectiveness of modern greenhouse systems to fulfill the demands of industrial food production. To comprehend these advancements, it is crucial to observe the many phases of progress [25].

2.1. Early Innovations Started and Developed in between (17th–19th Centuries)

- Pioneering Concepts: The creation of Dutch iconic "orange gardens" in the 17th century established the foundation for large-scale greenhouses. In the next period, greenhouse technological advancements began first in England and then in France [26,27].
- Focus on Exotic Plants: Initial applications primarily centered on cultivating luxurious and prized exotic plants, colonialization led to a concentration on cultivating valuable ornamental adaptive plants, reflecting new scientific curiosity and botanical interests.
- Industrialization Effect: Structural change arose because of the most fundamental breakthroughs of the Industrial Revolution. It made use of iron and steel frames, double glazing, and wood or coal-based steam heating systems, gradually growing output potential [26,27].

2.2. Commercial Expansion (20th Century)

Transition to Industrial Food Production: As food demand increased, the twentieth century saw a move toward growing crops every month of the year in large-scale commercial greenhouses and conditioned settings. Improved commercial transportation created the path for the distribution of certified food goods, and technical advancements hastened this transformation.

- The emergence of greenhouse vegetables: Fresh veggies, particularly tomatoes, cucumbers, and other high-value, high-consumption vegetables, are now available year-round. As a result of rising production speed, quality, and industrial needs in the greenhouse environment, these items have increasingly become commercially valuable greenhouse products around the globe [28].
- As soilless and "controlled environment agriculture" (CEA) techniques became more common in industrial agriculture, greenhouses improved productivity by allowing precise control over environmental conditions such as temperature, humidity, and nutrient distribution [28].

2.3. Modernization and Diversification (in the Twenty-First Century)

- Sustainability Concerns: As global environmental consciousness has grown, the energy utilized in greenhouses has led to the abandoning of traditional energy types in favor of alternative energy sources. It began to encourage the use of technology. Independent and, when appropriate, hybrid uses of renewable energy integration have evolved, particularly for solar, wind, heat pump, and related applications. Rising environmental concerns have prompted the use of water-saving methods [29,30].
- Expansion and Diversification: Large-scale specialized greenhouses to satisfy industrial needs have grown worldwide, adapting to varied climates and crops, and have begun to specialize in flowers, fruits, and even medicinal plants [28].
- The emergence of new systems and integration is evident in the adoption of innovative methods such as vertical planting and soilless integrated aquaculture agriculture (IAA) systems. These approaches, along with the increasing trend of regional production, provide opportunities for optimizing resources and integrating production with essential services in urban areas [30,31].

2.4. Future of Greenhouse Systems (Later Twenty-First Century)

The bright prospects of large-scale industrial greenhouses indicate that the further advancement of this crucial technology will likely be influenced by automation, robots, and artificial intelligence, with a specific focus on sustainability, climate resilience, and local food production [24]. These methods prioritize the importance of making enduring investments in industry and resources that will have a lasting influence on the future. In the latter half of the twenty-first century, there is anticipated to be substantial progress in technology and sustainable practices specifically in greenhouse systems. These innovations are designed to enhance efficiency, production, and environmental sustainability. Greenhouse systems in the future can incorporate a range of improvements, such as intelligent sensors, precision agriculture techniques, vertical planting structures, renewable energy sources, and carbon-neutral operations. These solutions strive to minimize the ecological footprint and adapt to changing climate circumstances. Key trends in the future of greenhouse systems may include the following:

- Integration of Internet of Things (IoT) and automation for real-time monitoring and control.
- Adoption of renewable energy sources like solar power for sustainable energy supply.
- Implementation of water-saving irrigation systems and nutrient management practices.
- Utilization of vertical planting and hydroponic systems to maximize space utilization.
- Incorporation of climate-resilient strategies to mitigate the impact of extreme weather events.

However, small-scale producers and farmers in developing countries still confront obstacles. Thus, research on small-scale businesses without large investments is necessary for sustainable food production for local market needs [24,25]. Future greenhouse systems should also increase output, resource use, and environmental resilience for small-scale farmers [2]. Future greenhouse systems for small-scale producers must be flexible to fit space constraints, cost-effective to install and maintain, and user-friendly to assure ease of use. Modern technology like automation, energy-efficient solutions, and water-saving irrigation should be used in these systems to optimize productivity and minimize waste. PETREE vertical planting systems demonstrate how small-scale growers can farm efficiently and sustainably in limited agricultural spaces. These solutions keep small-scale agricultural producers competitive and sustainable.

2.5. Pros and Cons of Industrial Greenhouse Systems

Traditional greenhouses control temperature, humidity, and light, but they may not meet crop needs. This may restrict crop growth [32]. Industrial greenhouse systems have several benefits and are predicted to remain vital to modern agriculture. However, several restrictions or downsides remain. The main constraints are high upfront capital and operational costs, dependence on non-renewable energy sources, suboptimal land utilization, water scarcity and management issues, pests and diseases, restricted biodiversity and ecosystem benefits, food safety risks, and social and ethical factors. Materials, climate control energy, and manpower are expensive to build and operate big industrial greenhouses [30]. This hinders smaller producers financially and accessibly. Energy-intensive large-scale greenhouse systems use artificial lighting, heating, and cooling to optimize growing conditions. This raise running expenses and emits greenhouse gases. Industrial greenhouse systems can regulate the growing environment, offering higher yields than open-field agriculture and protecting crops from extreme weather. They are susceptible to pest and disease outbreaks without chemical insecticides [33].

Large-scale greenhouse systems demand a lot of labor for planting, harvesting, and maintenance [34,35]. Large-scale greenhouse systems also have limited layout and design flexibility, which limits crop kinds and space use. Future technological and sustainable techniques may overcome these limits. This may involve more efficient and cost-effective greenhouse designs, sustainable energy sources, better water management, and natural insect control. The industry may also adopt more ethical and socially responsible strategies. Industrial greenhouse systems provide many benefits, but they also present considerable challenges that must be overcome for long-term sustainability and ethical operation [26,36].

2.6. Vertical Planting Systems (VPS)

Vertical Planting Systems (VPS) are an emerging agricultural technique that allows for plant production in vertically arranged layers, optimizing space utilization in urban and unconventional settings which means it is new mode of plant cultivation. As urbanization and world population continue to rise, it has become obvious that horizontal agricultural areas alone would not be enough to meet the increasing demands. Consequently, there is a growing need to explore alternative options. Within this specific framework, VPS systems that effectively incorporate significant optimal solutions hold great potential [37]. VPS, which have gained significant traction in industrial agriculture during the 21st century, consist of multi-layered structures that facilitate the cultivation of high-yield crops using hydroponics or aeroponics for nutrient distribution, both indoors and outdoors [30,38].

Vertical Planting Systems, as defined by [28,29] refer to enclosed structures that provide artificially controlled settings for agricultural cultivation. These systems operate continuously, allowing crops to be grown throughout the year and around the clock. They typically rely on soil-based production and standard watering methods [30,38].Vertical planting systems (VPSs) are viewed as a promising solution for the future of humanity and urban agriculture (Table 1). They emphasize the potential of VPS in terms of food security, resource efficiency, and creativity. Conversely, significant problems of energy usage, economic sustainability, limited profitability, and carbon emissions compared to VPS immobile agricultural systems are highlighted [28,39]. Is the future of urban agriculture promising discussions about sustainable agriculture becoming prominent, providing an answer to the adoption of vertical planting systems? This issue stays unresolved.

Table 1. VPS comparison with Traditional Planting System [24,25,28,29,39].

Aspect	Vertical Planting System	Traditional Planting System
Space Utilization	High, utilizes vertical space efficiently, suitablefor urban areas with limited land.	Requires significant horizontal land area, making it less suitable for urban environments where space is limited.
Production Efficiency	High yields per unit area due to controlled environment and intensive production methods.	Yields depend on soil quality, weather conditions, and traditional farming practices; may be lower per unit area compared to VPS.
Resource Consumption	Can be highly resource-efficient with optimized water and nutrient delivery systems.	Potentially more water and nutrient wastage due to less precise delivery methods.
Initial Investment	Relatively high due to complex infrastructure and technology needs	Lower initial investment as it requires simpler infrastructure and equipment.
Operational Costs	Can be variable depending on energy consumption, labor, and technology maintenance.	Generally lower operational costs but can be labor-intensive depending on the scale and mechanization of the farm.
Crop Suitability	Suitable for leafy greens, herbs, and some small fruits.	Suitable for a wide variety of crops, including root vegetables, grains, and orchard fruits which may not be feasible in VPS.
Climate Independence	More independent of external climate due to controlled environment.	Directly dependent on external climate conditions, making crops vulnerable to weather extremes and seasonal variations.
Social and Environmental Benefits	Promotes local food production, reduces transportation emissions, and improves urban green spaces.	Requires more land and can lead to deforestation and loss of natural habitats; however, it supports biodiversity in agricultural ecosystems if managed sustainably.

Vertical Planting Systems (VPSs) allow nutrients for plant growth to be transferred to plant roots through hydroponic or aeroponic systems within the VPS. These systems can also be used both indoors and outdoors, in controlled situations or by seamlessly integrating into buildings. In the future, VPSs are likely to become integral components of architectural structures. Is it possible to integrate the system into new architectural structures due to the low area efficiency that allows agricultural production to be maximized per unit area? [40].

VPS is also particularly well-suitable for contemporary metropolitan environments with limited land availability [41]. Climate control refers to the use of controlled settings to permit year-round production and protect against external weather fluctuations, particularly in the context of a changing global climate. By exercising meticulous regulation over water usage and optimizing nutrient allocation, it is possible to minimize wastage and enhance efficiency naturally. The incorporation of sensors and automation can decrease labor requirements and enhance the efficiency of manufacturing operations.

2.7. Traditional Planting Systems, Greenhouses, and Vertical Planting Systems Comparison

Table 2 offers a broad summary of four key areas next to conventional agriculture; VPS conserves the most water. Water consumption is highest in traditional planting, and greenhouses. Greenhouses and VPS utilize more energy than traditional agriculture owing to regulated settings and lights. Integrating renewable energy is crucial. Due to its vertical shape, VPS requires the least land use, followed by greenhouses. Food production in traditional agriculture uses the most land. Even if energy level, location, and other factors affect carbon footprint, greenhouses systems have the largest. The level will drop if the VPS uses renewable energy like solar, wind or alternative ones [41].

Table 2. Traditional Agriculture, Traditional Greenhouse, and Vertical Planting Systems Comparison [25,28,39,42,43].

	Traditional Agriculture	**Traditional Greenhouse System**	**Vertical Planting System (VPS)**
Water Consumption	Moderate-high (varies with crops and practices)	High (intensive irrigation, potential water stress)	Potentially low (closed-loop system, precise delivery)
Energy Consumption	Moderate (pumping machinery)	Moderate (climate control, lighting, machinery)	High (controlled environments, lighting)
Land Use	High (large areas, potential deforestation)	Moderate (greenhouses, land availability considerations)	Very low (vertical layers, urban suitability)
Carbon Footprint	Variable, depends on practices, transportation, and land-use change	High (energy use, potential deforestation)	Potentially low (renewable energy, reduced land impact)

Emerging technologies, such as precision agriculture, renewable energy integration, and enhanced climate control systems, have the potential to enhance the sustainability and efficiency of various systems. Sustained research and development are essential for maximizing performance, minimizing adverse effects, and ensuring the long-term sustainability of any planting system. The most favorable selection for food production is contingent upon economic circumstances and the initial rate of investment. The optimal choice of planting system depends on numerous factors, including specific context, resource availability, economic feasibility, and desired outcomes. A one-size-fits-all approach is not applicable [28]. Furthermore, the outcome of the targeted product is contingent upon the specific setting, availability of resources, and established priorities. Combining the strengths of different planting systems and integrating local initiatives can contribute to a more resilient and adaptable local food system, addressing economic and social concerns [42].

Currently, the production of food relies on the efficient management of economic factors and the involvement of local initiatives. Ultimately, the integration and examination of all advantages and the closure of significant drawbacks across many systems will enhance the long-term viability and adaptability of the local food system [43]. This also entails the implementation of precision farming techniques aimed at reducing water and fertilizer consumption, as well as the adoption of integrated pest control approaches aimed at minimizing pesticide usage.

3. Sustainability Futures in Planting Systems

Sustainability management in horizontal and vertical greenhouse systems refers to the process of efficiently handling the significant inputs and outputs in a production setting. Regardless of whether they are conventionally placed horizontally or in more contemporary vertical systems, all planting systems generate several primary forms of output as follows.

a. Organic waste refers to the byproducts of plants, such as plant debris, food leftovers, and other organic matter. If not handled appropriately, these materials can become waste which is as critical as the planting outputs and can easily be converted into valuable assets [44].
    1. Composting is a highly effective method for converting plant remnants, trimmings, manure, and more agricultural refuse into compost that is abundant in nutrients. It is effective in domestic gardens, small-scale farms, and large-scale agricultural operations. The utilization of compost and organic fertilizers derived from agricultural waste enhances soil fertility, increases crop output, and perhaps obviates the necessity for synthetic chemical fertilizers [44].
    2. Biogas production is a highly efficient approach to waste management, particularly in underdeveloped nations. Waste is converted into biogas, a renewable energy source that may be used for cooking, heating, and generating electricity. The EU is promoting the implementation of extensive biogas production to effectively handle agricultural waste and enhance sustainable agriculture. Biogas effectively manages agricultural waste and generates cleaner, more efficient energy, reducing air and water pollution and enhancing quality of life [45].
    3. Mulching is the practice of applying organic materials or plastic to the soil surface to retain moisture and suppress weed growth. Utilizing agricultural solid waste as mulch aids in the preservation of nutrients and moisture, and the inhibition of weed proliferation. Mulching safeguards the soil from erosion and fluctuations in temperature, thus enhancing the well-being and production of crops. Utilizing agricultural waste as mulch helps to preserve soil moisture [43].
    4. Biomass conversion involves the transformation of organic materials, such as plants or agricultural waste, into electricity or other valuable products. Thermochemical and biochemical conversion processes transform agricultural waste into biofuels, biochemicals, and bioplastics [45].
    5. Combustion is the process of burning biomass to produce heat and energy. Due to the emission of carbon dioxide into the carbon cycle, fossil fuel combustion is considered less sustainable compared to other methods.
    6. Fermentation is the process by which crops, sugarcane are transformed into biofuels such as ethanol or biodiesel. They provide a more sustainable alternative to fossil fuels in transportation and other industries.
    7. Pyrolysis is a process that involves heating biomass in the absence of oxygen to produce biochar, bio-oil, and syngas. Biochar can enhance soil fertility, whereas bio-oil and syngas can be converted into biofuels and other valuable commodities [45].

b. Gasification is a process that transforms biomass into syngas through partial oxidation. Syngas can produce electricity or can be converted into chemicals and liquid fuels.
c. Proper disposal of chemical waste is necessary for pesticides, fertilizers, and cleaning products.
d. Output water, the term "greenhouse, output water" refers to the amount of freshwater that becomes contaminated during its usage and needs to be treated before being released back into the environment. Within greenhouses, this covers water that has become polluted with fertilizers, insecticides, and other chemicals that farmers use for cultivation. To minimize greywater, one must use strategies such as integrated pest management and effective nutrition management to decrease the amounts of contaminants [46].
e. Harnessing greenhouse waste heat in sustainable systems, greenhouses generate substantial heat through the absorption of sunlight and the use of heating devices. The heat generated in conventional greenhouse systems is energy that is not utilized efficiently. Currently, modern methods can harness this thermal energy and utilize it for many sustainable applications. Three fundamental criteria can be used to assess the correct utilization of energy [11].
    1. Direct connection: Establish a physical link between greenhouses and adjacent structures (such as residences, schools, etc.), using insulated pipes to directly transmit heat.
    2. District heating systems involve the integration of greenhouses into larger networks to provide heat to many buildings in a neighborhood.
    3. Heat pumps are utilized to capture heat from the air inside a greenhouse and transfer it to other buildings at elevated temperatures.

In this approach, sustainable agriculture is increasingly being aligned with organic/clean products. Sustainability and waste management in greenhouse systems aim to reduce waste and maximize resource consumption. This goal involves conserving water, energy, and other resources, reducing greenhouse gas emissions, and managing greenhouse waste. Sustainability means minimizing environmental harm, preserving resources, and promoting biodiversity to maintain ecological equilibrium and productivity [43]. Garbage management in greenhouse operations involves reducing, recycling, and disposing of garbage. These characteristics are crucial for decreasing environmental impacts and ensuring agricultural sustainability. This includes accepting renewable energy sources, optimizing water use, reducing chemical inputs, and recycling and composting. Sustainable practices and waste management can reduce greenhouse operations' environmental impact and help preserve the ecosystem.

3.1. Reusing Packaging Materials in Greenhouse System

Polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) are examples of different types of polymers that serve as the fundamental construction materials for horizontally erected small-scale greenhouse systems [47]. These materials are commonly utilized in impoverished regions, which refers to locations with restricted access to resources, technology, infrastructure, and other essential aspects needed for effective and profitable agricultural activities in undeveloped countries [6]. The main construction material used to produce low-covered awnings, which is the preferred choice among small-scale garden manufacturers, primarily consists of plastic pipes, coverings, and connectors. In addition, other low-cost plastic materials are used for a variety of purposes, such as making pots, trays, mulch film, and irrigation tubing. Recycled plastic components are commonly used in the manufacturing of industrial plant and flower products, as well as in pot packs that can be transported worldwide, demonstrating their versatility. Small-scale garden production in underdeveloped areas often relies on plastic films of varying thicknesses and colors as the main cover material, as they are very convenient and versatile [32]. The increasing use of plastic in trade raises concerns about its environmental impact and the generation of waste. Furthermore, agricultural operations utilize a variety of plastic materials, including containers, bags, and packaging, to assist in planting, harvesting, and transporting crops. Many sustainable greenhouse systems, whether built vertically or horizontally, still heavily rely on the presence and use of plastic derivatives. In the context of industrial agriculture, a comprehensive list of potential applications for various types of plastic derivatives in basic greenhouse systems is provided in Table 3 [38].

Table 3. Possible Plastics and Derivatives in Greenhouse System [32,38].

Category	Type	Material	Function	Environmental Impact	Reuse Strategies
Containers	Pots	PP, PE, HDPE (high density polyethylene)	Growing seedlings plants	Leaching of chemical pollution	Reusable pots, washing and reuse systems, biodegradable pots
	Trays	PP, PE, HDPE	Transplanting seedlings, supporting pots	Same as pots	Same as pots
	Packs	PE, PVC	Sowing seeds, starting seedlings	Same as pots, potential PVC toxicity	Biodegradable alternatives, reusable trays
Mulch and Covers	Film Mulch	PE, LDPE (low density polyethylene)	Suppress weeds, retain moisture, regulate temperature	Microplastic pollution, non-biodegradable	Biodegradable mulch films, perforated mulch for reuse, cover crops
	Row Covers	PE, LDPE	Protect crops from pests, weather	Same as film mulch	Same as film mulch
	Greenhouse Structures	PVC, Polycarbonate	Building greenhouse frames, panels	Limited recyclability, potential PVC toxicity	Durable materials, designed for disassembly, explore alternatives
Irrigation	Tubing	PE, PVC	Transporting water throughout the greenhouse	Same as greenhouse structures	Durable materials, leak repairs, explore alternatives
	Connectors	PE, PVC	Connecting irrigation components	Same as tubing	Same as tubing
Other	Shrink Wrap	PVC, PE	Securing transplants, bundling products	Same as greenhouse structures	Minimize use, explore alternatives
	Netting	PE	Insect netting, bird netting	Microplastic pollution, non-biodegradable	Durable materials, repair damaged nets, explore alternatives

Disused plastic containers, trays, and mulch film, when discarded, make a substantial contribution to both landfill debris and microplastic pollution. Undoubtedly, the implementation of rational plastic management and efficient recycling is crucial for ensuring a healthy future. An extremely strict waste recycling framework should be implemented to gather and categorize plastic waste, which can subsequently be converted into new products or utilized as fundamental elements in manufacturing [25]. An agricultural company should actively engage in recycling efforts to make a substantial contribution to the circular economy. Manufacturers can decrease the demand for fresh plastic materials and contribute to the conservation of precious fossil fuel resources [1].

3.2. Long-Term Plastic Sustainability in Greenhouse Production

Reducing/Minimizing use is a highly efficient approach. Reducing plastic consumption at its origin is possible through the adoption of techniques such as utilizing reusable flowerpots, implementing efficient watering systems, and minimizing packaging [45].

Reuse/Implementing wash and reuse systems can help extend the lifespan of pots, trays, and irrigation lines, hence reducing waste [44].

Recycling Establish collaborations and build necessary facilities to efficiently gather, categorize, and reprocess greenhouse plastics for recycling purposes. Society for Horticultural Science.

Biodegradable plastic considers and use biodegradable plastics derived from plant-based resources like PLA or biopolymers as substitutes to prevent persistent plastic pollution.

The New Plastics Economy is a concept that promotes a circular economy for plastics. Closed-loop solutions involve the design of greenhouses that incorporate plastic recycling facilities to decrease waste and encourage circularity [1,2]. The concept of circular economy in plastics refers to the establishment of a novel economic system centered on the principles of design, recycling, and innovation specifically applied to the realm of plastics. The evaluation of reducing plastic consumption in sustainable greenhouse systems can be categorized into two primary aspects for the near future.

1. Reduce/involve utilizing existing plastic derivatives and developing alternative materials with lower carbon footprints to minimize consumption.
2. To establish waste management methods that facilitate the utilization of recycled or used plastic materials in greenhouse manufacturing without the need for further recycling.

Specifically, the utilization of plastic waste material can yield significant cost reductions, particularly for small-scale producers, farmers, and sustainable horticultures, in areas with limited resources, who face substantial initial investment and operational expenses associated with greenhouse production.

3.3. Possibilities of Reusing "Obsolete" Plastic Products in Agriculture

Table 3 reveals a significant presence of various plastic and plastic-derived components in contemporary greenhouse systems, whether horizontal or vertical, traditional, or industrial. There are alternatives to the extensive use of plastic on an industrial scale, such as reusing, reducing, and recycling, as well as developing new alternative materials in a sustainable manner. Certain products, particularly for producers of tube or potted plants, are essential. These products include flowerpots, pot trays, various covers, and shrink materials for packaging. Plastic is extensively used in agriculture, especially in small-scale greenhouses in impoverished regions or developing countries. Transitioning current plastic products to a more environmentally friendly framework could be a crucial step. Working on plastic materials has the potential to increase production efficiency, reduce carbon and water footprints, and promote a more sustainable future [38]. Global trade requirements demand materials that are lightweight, environmentally friendly, and compatible with full chemical recycling processes. The use of plastic materials is facing stricter regulations. Achieving the necessary outcomes may involve altering the composition or source of the materials used [30,32]. There are three options for implementing this plan:

1. Designing or selecting long-lastingproducts, plant pots, pot trays, and other similar products that will be utilized in the greenhouse.
2. Selecting eco-conscious options (such as biodegradable materials) and examining the characteristics of consumer goods derived from organic waste.
3. The changeover process can be achieved by predominantly advocating for the use of recycled samples in practical applications.

The widespread utilization of plastic in agriculture, namely in greenhouses, is causing significant worries regarding its environmental impact and the accumulation of waste [37]. However, plastic presents encouraging resolutions for a progressively sustainable future.

This text analyzes the various options, possibilities for future development, and scholarly discourse surrounding five significant alternatives.

3.3.1. Reusable Pots and Trays

Modular pot and pot traydesigns and systems are being used to enable convenient disassembly and reusability for washing and commercial purposes. These systems of modular components are constructed using pots and pot trays produced from robust and fully recyclable plastics, like HDPE or PP. Dutch flower farmers have achieved a stage where they are able to reuse modular plastic pot trays over 100 times through appropriate washing and disinfection. Modular potting systems, which are developing self-cleaning or antimicrobial coatings for plastic pots could serve as an alternative solution to further mitigate water and hygiene issues resulting from reuse. Research on circular economy practices in plastics and the introduction of a "new economy model of plastics based on design, recycling, and innovation" highlight the economic and environmental interplay of reusable plastic systems [1].

3.3.2. Recycled Plastic Mulch Films

The production of mulch films, which are used in industrial greenhouses within large surfaces, can take another important step toward a more sustainable greenhouse model by promoting the use of materials made from recycled plastics. In the coming years, the use of bio-degradable and perforated mulch films that may easily biologically degrade may become more widespread. For instance, major manufacturers like "Tri-Wall"offer recycled alternative mulch films, while brands like "BioAgri" are developing new biologically degradable options. Additionally, it may soon be possible to achieve more sustainable results, such as crop mulch film production, by using organic waste.

3.3.3. Biodegradable Plastic Alternatives

Biodegradable plastics derived from plant-based resources, such as PLA or biopolymers, are becoming more prevalent in the production of flowerpots, pot trays, and mulch films. Their utilization offers a more sustainable and eco-friendly approach for the future. For example, companies like Ecopots and Vegware have initiated the production of biodegradable pots and potting trays. Users have the option to utilize biodegradable mulch films provided by BioAg and Nature Works enterprises. Extensive research on enhancing the efficiency and cost-effectiveness of biodegradable plastics is essential for their widespread acceptance, given their significant potential for promoting environmental sustainability [46].

3.4. Future Possibilities of Plastic Usage in VPS

Plastic usage in greenhouse planting systems has been a prevalent practice for many years, offering numerous benefits such as climate control, pest management, and increased crop yields. In academic discussions, the future possibilities of plastic usage in greenhouse planting systems are likely to continue evolving to address sustainability concerns, technological advancements, and environmental impacts [40].

3.4.1. Sustainable Plastic Alternatives

As concerns about plastic pollution and environmental sustainability grow, the future of plastic usage in greenhouse systems may involve the development and adoption of biodegradable or recycled plastic materials [48]. That also explores the potential of biodegradable mulching films in agriculture, indicating a shift towards more sustainable plastic alternatives in greenhouse operations.

3.4.2. Smart Plastic Technologies

Advances in smart materials and sensors could revolutionize plastic usage in greenhouse planting systems by enabling real-time monitoring of environmental conditions, crop health, and resource management. Research by Wu et al. [49] discusses the application of smart materials in agriculture, highlighting the potential for enhanced efficiency and productivity in greenhouse operations through smart plastic technologies.

3.4.3. Circular Economy Approaches

The future of plastic usage in greenhouse systems may also involve the adoption of circular economy principles, where plastics are recovered, recycled, and reused within closed-loop systems. Studies emphasize the importance of circular economy approaches in reducing plastic waste and promoting sustainability in agricultural practices, including greenhouse cultivation [50,51].

3.4.4. Nanotechnology Applications

Nanotechnology offers promising opportunities for enhancing the performance and sustainability of plastic materials used in greenhouse systems. Research by Khan et al. [52] discusses the potential of nanocomposite materials for agriculture applications, indicating the possibility of utilizing nanotechnology to improve the properties and lifespan of plastic components in greenhouse structures.

3.4.5. Carbon Footprint Reduction

Future advancements in plastic usage in greenhouse planting systems may focus on reducing the carbon footprint associated with plastic production, usage, and disposal. Research by Notarnicola et al. [53] highlights the importance of life cycle assessments in evaluating the environmental impacts of plastic materials in agriculture, providing insights into strategies for mitigating greenhouse gas emissions in greenhouse operations.

By incorporating these innovative approaches, greenhouse operations can become more environmentally friendly, resource-efficient, and resilient to future challenges, contributing to the long-term sustainability of agriculture. Further research and interdisciplinary collaborations will be essential in exploring and implementing these potential future possibilities of plastic usage in greenhouse planting systems.

4. Introduction PETREE

As global changes occur, irregular rainfall patterns and structural changes could lead to problems in irrigation and water scarcity. As a result, agricultural efficiency and sustainability have become more important for meeting rising demands and ensuring long-term future success. It is crucial to protect small producers who are the foundation of fresh production and boost their output, continuity, and efficiency. This is essential for both developed and emerging countries, as well as regional economies. The PETREE mobile vertical growth kit is a modular, practical, and environmentally friendly technology that maximizes the use of limited resources and aims for minimal resource consumption and maximum efficiency in small-producer crop farming. It also meets the fresh plant needs of home users. The Petree vertical planting system is a low-cost transportable vertical greenhouse system that specializes in flower planting and fresh food production in regions with limited resources and space. The design principles of the PETREE system favor the maximum possible use of old PET packaging and recycled plastic components. This design strategy addresses the demands of small-scale garden producers, particularly those in rural locations with limited resources, to help them transition to an environmentally friendly greenhouse system.

The PETREE design system can be perceived as a comprehensive vertical plant production system (VPS). However, it can also be defined as a micro-scale, independent vertical planting system in terms of appearance and usage principles. Therefore, it's a new hybrid system that can be produced for small producers by creating a conditioned environment that adapts to all types of land cover, including lands that do not have agricultural characteristics. As a result, PETREE is a new, innovative modular system that combines the practical and effective solutions of both worlds (Figures 1 and 2).

Figure 1. The components and principles of PETREE product.

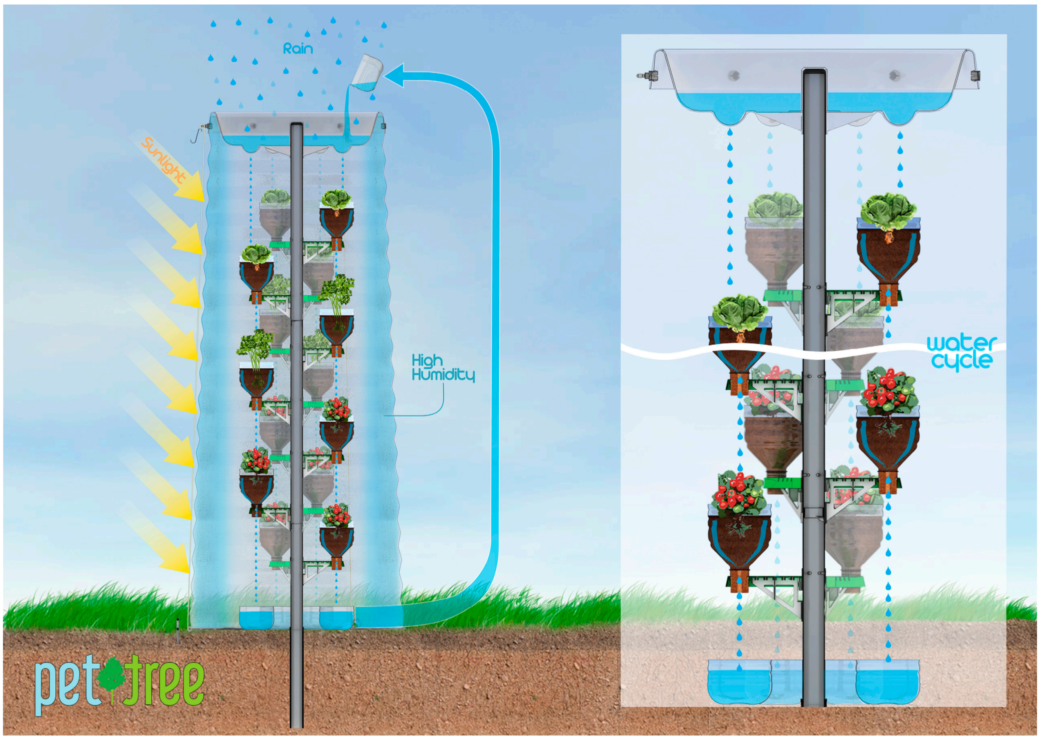

Figure 2. Working principles of PETREE station.

4.1. Design Principles and Potentials

PETREE (5 lt. PET) packs are designed as a portable and modular cultivation system that is suitable for drip irrigation, based on the reuse of waste materials within a multi-layered, vertical sustainable farming system (Figure 2).

1. The PETREE system is specifically developed to accommodate the needs of both rural and urban areas.
2. The system consists of multiple portable stations that may be quickly set up on different terrains, including small and narrow areas that are too uneven and fragmented to accommodate an effective greenhouse.
3. The Petree system offers straightforward installation and transportation possibilities with its autonomous station design and modular structure.
4. The design aims to optimize convenience by ensuring quick assembly, disassembly, part replacement, and maintenance in a compact package.

5. Independent stations are self-contained plant cultivation systems that utilize drip irrigation. They employ waste PET bottles, namely 5 L, in this project, which are positioned vertically in a multi-layered and staggered configuration.
6. Each station has been purposefully engineered to collect rainwater or maintain output within a closed system, utilizing a limited amount of water through the principles of drip irrigation. The optimal capacity of these stations is to minimize both water and energy losses.
7. Mobility potential allows small producers, especially those with limited land, to sustain their output levels by improving the productivity of their unused land.
8. The Petree system, characterized by its autonomous station design and self-contained approach, can be tailored to sustainable agriculture, even in environments with limited land and infrastructure resources.
9. Closed units offer regulated environmental conditions, including control overheat, light, and humidity. PETREE's separate unitary and closed system structure ensures effective utilization and conservation of water and heat inputs. In addition, it collects any surplus irrigation water at the base, which is beneficial in situations when both water conservation and a moist atmosphere are desired.
10. The system is specifically intended to be well-suited for use in dry environmental circumstances. It is highly sensitive to water usage, making it appropriate for both regular watering and drip irrigation.
11. The system possesses the capacity to adjust and conform to various usage conditions (such as luminosity, thermal insulation) By adjusting the tint of the outer cover to match the specific light requirements of each plant, we can regulate its permeability.
12. PETREE is very suitable for mid-industrial plant production. In terms of manufacturability, the PETREE system is suitable for the existing low- and medium-quality industrial infrastructures of developing countries. The materials used have been selected to be highly compatible with recycling.
13. Overall, the system design of PETREE fulfilled the user-friendly design approaches and sustainability principles.
14. In addition, it provides the opportunity to eliminate potential diseases and similar problems in the most harmless and economical way.
15. Petree stations have a specific engineering that enables natural gathering and accumulation of rainfall.
16. Furthermore, it will prove to be a very efficient remedy for ensuring product safety and safeguarding against animal interference.

4.2. Assembly of a System UNIT

The independent unitary structure of the PETREE system allows the installation of any number of stations and their flexible deployment depending on the requirements. The placement of the products is determined according to the site layout plan, considering the installation needs, regardless of the topographic structure and shape of the area.

The independent assembly process of each product begins with the placement of the main carrier in the ground plane of the pole. In the second stage, the necessary plastic components of the system are combined and positioned. The water collection reservoir is located at the top of the system. In the next stage, the vertical system is strengthened by various means. The PETREE system's vertical greenhouses offer distinct advantages compared to other systems, including their autonomous, easily transportable, and simple-to- place transparent outer protective cover and added tension elements (Figure 3). The collected PET (Polyethylene Terephthalate) bottles are cut into the desired size (between 1.5 and 4.5 L) and according to the plant to be grown and made ready for reuse. They then place these used bottles in a vertical position, upside down and diagonally to serve as production containers. The cut bottom pieces of PET packages are placed on the bottom of the system and used to collect water and humidify the closed environment.

Figure 3. Assembled vertical planting unit module "Petree".

4.3. Technical Specifications for the PETREE System

The PETREE system boasts a comprehensive technical design that revolves around a standardized infrastructure, specifically tailored for streamlined manufacturing processes using widely accessible plastic injection molding techniques commonly found in developing nations. Most system components can be efficiently fabricated using injection machines with a printing capacity of 200 g (Figures 3 and 4). Notably, the sturdy metal support structure is crafted from materials known for their resistance to corrosion, such as galvanized steel or aluminum. The greenhouse membrane covers are meticulously fashioned from nylon derivatives, offering a diverse range of color options to cater to the unique requirements of various plant species. In terms of cost analysis, the estimated expenditure per station, inclusive of packaging, is approximately EUR 40.. It is important to highlight that this cost projection excludes the repurposed 5-L PET containers, as the PETREE system is designed to repurpose discarded materials, aligning with sustainability principles and environmental consciousness. A practical field study was conducted in collaboration with tomato producers operating within an industrial setting. The implementation of the PETREE system involved consolidating three tubes of industrial pole tomatoes into a single location within the system. This operational optimization is anticipated to result in a significant yield ranging between 80 and 100 kg of tomatoes. Furthermore, based on our calculations, the anticipated annual production output from three turns in a 2 decarearea year utilizing the 1200-unit station PETREE system is projected to generate substantial revenue. This revenue stream is expected to facilitate the recuperation of the initial investment cost associated with each station within a relatively short timeframe of approximately 1.5 years. The PETREE system's ease of packaging and potential for global marketability position it as a significant product. Its adaptability for clean energy integration makes it a versatile solution suitable for hydroponic and aquaponic agriculture. The system's flexibility enables seamless transition towards sustainable practices, aligning with the evolving demands of environmentally conscious consumers worldwide. For the future PETREE system will be considered as an alternative solution that allows ease of access for small-scale producers and urban consumers, providing convenience for all users.

Figure 4. Recycled plastic injection molding parts of the system.

4.4. Advantages and Possibilities of PETREE a New Hybrid VPS

These advantages include reduced dependence on existing infrastructure, effective water collection capabilities, enhanced disease control strategies, and suitability for both soilless farming methods and personal use. Additionally, the system features a logical and efficient cost structure. The selected plastic materials have been designed for a longer lifespan, improving the economic feasibility of the system. Furthermore, the PETREE system enables production in areas that are not suitable for traditional greenhouses, such as sloping terrain, damaged surfaces, nonagricultural soil, and other similar conditions. The estimated environmental degradation period for a discarded 5-L plastic bottle is approximately 90 years. By repurposing plastic waste, the PETREE system contributes to a sustainable solution for the persistent environmental challenge. Preliminary research indicates that the PETREE system offers significant benefits, supported by international evaluations. However, the comprehensive implementation and widespread adoption of this model in the field have not yet been realized. Consequently, without actual performance results, we lack reliable comparison values. In the next phase, evaluations such as the price performance ratio and plant type productivity ratio will yield data that will unveil the true value of the system. This will create a basis for comparison within the current sustainable horticultural environment.

4.4.1. Flexibility

PETREE as a new innovative VPS for sustainable horticulture fulfills all the required criteria for flexibility. The modular design enables versatile applications, ranging from household usage to the extension of functionality to small and medium-sized greenhouses. The PETREE system is also appropriate for cost-effective mid-level industrial agriculture and other planting requirements. The distinctive characteristic of being autonomous from land or landforms, and being constructed vertically above the ground plane, offers flood protection. The air circulation between the modules provides a superior alternative to the susceptibility of broad surfaces in traditional greenhouses to wind. Moreover, the Petree system has a reduced susceptibility to harm caused by intense precipitation, such as rain, snow, and hail, in comparison to conventional greenhouses (Figure 3).

4.4.2. Adaptability to Challenging Terrain

PETREE's modular and portable design enables it to be easily set up on many terrains, including small and uneven places that may not be suitable for traditional greenhouse structures. This adaptability to challenging terrain is a key feature of the most popular VPS variants. The primary benefit lies in the fact that the entire building is engineered as a transportable unit, enabling production to occur on small parcels of land, even ones that are unsuitable for agricultural purposes. This remarkable capability allows small-scale farmers to make use of previously unutilized or uncultivated lands, thus increasing production levels and agricultural productivity in areas with limited arable land.

4.4.3. Space Utilization

Vertical planting methods are designed to maximize space utilization, making them well-suited for places with limited land availability. Vertical farming enables the growth of crops in multiple layers, resulting in optimal yield within limited spaces [54,55]. PETREE optimizes vertical spatial utilization, rendering it well-suited for locations with restricted land availability, such as metropolitan and peri-urban zones. In poor regions where land is limited or costly, PETREE can empower farmers to optimize their land utilization efficiency and enhance agricultural output without necessitating extensive land areas.

4.4.4. Production Efficiency

VPS enhances agricultural growth and yields by creating controlled settings that accurately regulate elements such as light, temperature, and humidity [56]. PETREE systems can optimize crop productivity by employing controlled settings and intense production methods, resulting in high yields per small unit area. In poor regions, where farmers frequently face challenges in achieving maximum crop yields due to environmental limitations and limited resources, this solution presents a promising opportunity. It creates a favorable environment for plant growth, while simultaneously improving production efficiency and ensuring food security. Another significant advantage of the PETREE system is its ability to enhance production efficiency during periods when agricultural areas are not being cultivated. The flexibility provided by this feature is essential for small producers since it enables them to relocate individual modules or stations as needed, either on an optional basis or during specific seasons. Hence, the PETREE technology empowers conventional firms to transition to VPS, thereby enhancing productivity. Petree also incorporated an additional component that establishes a community without soil by utilizing environmentally friendly energy sources, such as solar energy, at each station, as well as aeroponics and hydroponics (Figure 5).

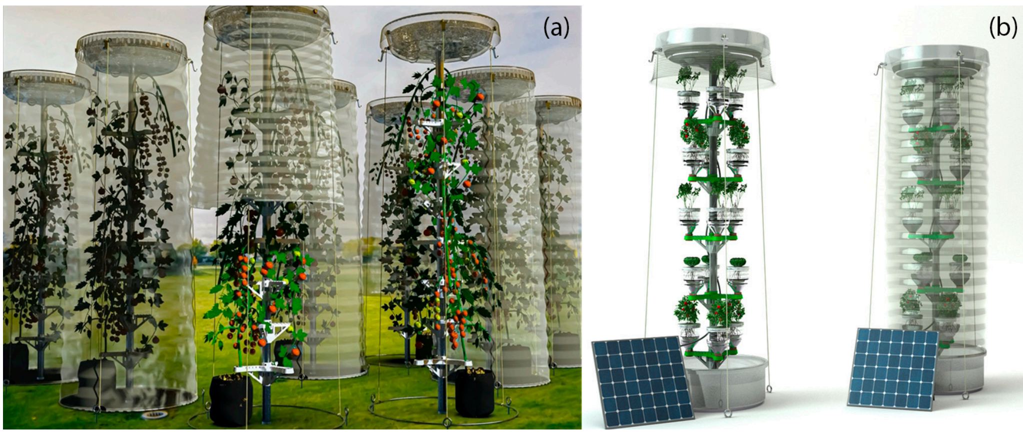

Figure 5. (**a**) Production application mid-level industrial tomato, (**b**) PETREE Station Application of Aquaponics Planting Systems.

Aeroponics is a method of growing plants without using soil. In this system, plant roots are exposed to a nutrient-rich mist or air environment. This allows for better oxygenation and nutrient absorption, leading to faster growth and higher yields compared to traditional soil-based methods. Aeroponic systems are commonly utilized in vertical farming and greenhouse setups to grow a variety of plants efficiently and sustainably [57].

Hydroponic farming is the practice of cultivating plants in a nutrient-rich water solution with their roots directly submerged in the solution. This method enables precise regulation of nutrients and water supply to the plants, leading to faster growth and higher crop yields compared to traditional soil-based farming [57].

The comparison made with two different greenhouse systems (traditional low and mid-scale greenhouse systems) as shown in Figure 6, gives an idea about the area usage and efficiency analysis of plant root per m2 system efficiency. From this comparison, an important variable is height, and as the height increases in the Petree system, production efficiency also increases.

Figure 6. Comparison of PETREE with Traditional low- and mid-scale greenhouse system.

4.4.5. Versatility and Customization

PETREE provides agricultural adaptability and customization by enabling the growing of many crops in both horizontal and vertical orientations while minimizing soil depletion. Additionally, it serves to offer flexibility and diversity. The modular design of this system enables effortless customization and adjustment to meet the specific needs of various crops, thereby making it highly ideal for a wide range of farming methods, including hydroponics (the growing of plants in water). Hydroponic agriculture is a soilless form of plant cultivation, in which plants obtain needed elements directly from water solutions. Hydroponic systems commonly utilize inert mediums such as perlite, rockwool, or coconut coir to assist plant growth. These mediums offer physical stability while enabling roots to obtain nutrients and oxygen [58].

4.4.6. Resource Efficiency

It is crucial for all VPS. It should integrate water and fertilizer delivery systems that are effective, such as hydroponics or aeroponics. These approaches help minimize water usage and reduce nutrient loss when compared to traditional farming methods [59]. PETREE is a novel VPS that focuses on utilizing waste materials, including old PET packaging, and recycled plastic components, as a priority in its design principles. This strategy optimizes resource efficiency while maximizing the exploitation of the scarce resources accessible to small-scale garden growers in rural areas. PETREE systems are specifically engineered to optimize resource utilization. By implementing efficient water and nutrient delivery systems in impoverished regions with limited access to these resources, it is possible to conserve resources by limiting wastage of water and nutrients. Additionally, this approach can reduce reliance on chemical inputs like fertilizers.

4.4.7. Closed-Circuit Autonomous Stations

PETREE's closed-circuit autonomous stations function as self-contained plant-growing systems equipped with drip irrigation capabilities. These stations have a closed-loop technology that reduces water and energy losses, making them well-suited for regions experiencing water scarcity or unpredictable rainfall patterns. Petree also incorporated an accessory that establishes a soilless environment by utilizing sustainable energy sources, such as solar energy, at each station as well as aeroponics and hydroponics. PETREE demonstrates excellent heat efficiency and moisture protection capabilities, making it very compatible with heat pump systems. The contrast depicted in Figure 5 provides insights into the utilization of space and the study of efficiency in traditional low and mid-scale greenhouse systems, namely in terms of plant root per square meter. Based on this comparison, height is identified as a significant factor, with an observed correlation between increased height in production stations and improved production efficiency.

4.4.8. Pesticide and Disease Control

PETREE's closed-loop technology and controlled environment effectively mitigate the risks of pests and illnesses, ensuring natural protection. PETREE decreases the necessity of chemical pesticides by avoiding contact with external infections and pests. PETREE's vertical form facilitates enhanced air circulation, effectively inhibiting the accumulation of humidity and moisture that commonly foster the proliferation of fungal illnesses.

PETREE's modular construction allows for the use of integrated pest management (IPM) strategies, such as companion planting and biological control measures. These solutions additionally decrease the dependence on chemical pesticides while fostering ecological equilibrium within the system.

4.4.9. Climate Adaptability

VPS can be engineered to be adaptable to climate change, incorporating climate-controlled spaces and protective buildings that safeguard crops from unfavorable weather conditions, enabling cultivation throughout the year [60]. PETREE systems ensure climate resilience by creating a regulated environment for cultivating plants in regions that are susceptible to climate change and severe weather conditions. PETREE can minimize the potential dangers linked to crop losses by offering a secure and sheltered cultivation setting, hence augmenting resilience and adaptation. Various material modifications can effectively preserve and fulfill the capacity for adaptability to different environmental circumstances, hence generating flexibility.

4.4.10. Enhancing Livelihoods

Vertical planting methods have the capacity to enhance income opportunities for farmers in impoverished regions by facilitating year-round cultivation of high-value crops and minimizing reliance on weather conditions. This, in turn, aids in poverty alleviation and promotes food security [59]. PETREE systems have the capability to provide year-round cultivation of lucrative crops, hence generating supplementary sources of revenue for farmers residing in impoverished regions. Diversifying income sources and enhancing agricultural production can effectively contribute to poverty alleviation and promote sustainable rural development in impoverished communities. Furthermore, this approach is highly compatible with sustainability solutions at the level of individual households.

4.4.11. Cost Effectiveness and Availability

The PETREE system offers a significant advantage over typical VPSs in terms of cost-effectiveness and availability. Due to the system's flexibility, small producers have the option to purchase it in separate components, resulting in a relatively cheap initial investment and ongoing expenses. Cost-efficient system solutions like PETREE can serve as excellent tools for delivering credit support and help to NGOs, as they yield favorable outcomes across many applications. PETREE's cost structure is economically efficient, which allows small producers without access to traditional loans or financial support to afford it. It provides an affordable alternative to conventional small-scale farming and traditional greenhouse systems, enabling small-scale farmers to embrace sustainable farming methods and enhance their quality of life.

4.4.12. Operational Cost Efficiency

It is another key advantage of systems like PETREE, encompassing factors such as ease of installation, labor requirements, and maintenance. PETREE's modular and portable design facilitates straightforward setup, reducing installation time and labor costs for users. Additionally, the system's user-friendly interface and minimalistic structure contribute to ease of operation, requiring less manpower for maintenance and day-to-day management. Furthermore, PETREE's emphasis on durability and reliability minimizes the need for frequent repairs, further reducing long-term operational expenses. By optimizing operational costs, PETREE enables users to allocate resources more efficiently, maximizing returns on investment and promoting sustainable agricultural practices.

4.4.13. Energy Consumption and Carbon Footprint

Vertical planting systems often use hydroponic or aeroponic cultivation methods, which require less land and water compared to traditional farming, resulting in reduced carbon emissions [60]. PETREE also has significant benefits in terms of energy consumption due to its minimal power usage. As a self-contained system, it operates independently without needing additional energy sources like artificial lighting or heating. The design of PETREE focuses on utilizing solar energy for water circulation and natural ventilation, leading to efficient use of natural resources to create ideal growing conditions for plants without relying on external energy inputs, especially in semi-industrial applications. PETREE's operation eliminates the need for energy-intensive components, resulting in a significant reduction in energy consumption compared to conventional greenhouse systems. This makes PETREE a sustainable and environmentally friendly choice for agricultural production, as it emphasizes using recycled materials and minimizing resource consumption to reduce carbon emissions associated with manufacturing and disposal processes. By promoting local production and consumption of fresh produce, PETREE helps reduce carbon emissions related to transportation and distribution networks. Additionally, implementing sustainable agricultural practices within PETREE systems, such as organic farming methods in urban areas and soil carbon sequestration, can help mitigate greenhouse gas emissions and improve carbon sequestration in agricultural soils.

4.4.14. Adaptability in Rural Environment

The PETREE system offers exceptional adaptability and usability in urban environments, making it a highly adaptable solution that effectively caters to the requirements of urban consumers. The system distinguishes itself from its equivalents based on the following categories:

a. Space utilization: PETREE's vertical planting technique optimizes space utilization in densely populated metropolitan areas with limited land availability by effectively exploiting vertical space. Urban farmers can cultivate crops in compact areas like rooftops, balconies, or vacant indoor spaces.
b. Resources efficiency: PETREE's design prioritizes resource efficiency through the implementation of efficient water and nutrient distribution systems. This is particularly crucial in urban settings where resources like water and land are limited. PETREE reduces water use and limits the discharge of nutrients, making it an environmentally viable option for urban agriculture.

c. Local food production: PETREE enables urban inhabitants to cultivate fresh produce in their local area, thereby diminishing the carbon emissions linked to the transportation of food from rural regions to cities. This enhances the stability and ability of urban residents to access food while decreasing reliance on distant food distribution networks.
d. Community engagement: PETREE systems in urban contexts can function as platforms for community interaction and education regarding sustainable agriculture. PETREE fosters a feeling of camaraderie and a strong bond with the natural world in urban settings by uniting individuals through the cultivation of food.

4.5. Assessment of the Potential Benefits and Implementation of the PETREE System in Developing Countries Similar to Turkey

In the context of countries like Turkey's agricultural landscape, which is characterized by rapid population growth in the agriculture sector and the subdivision of land into smaller parcels due to inheritance practices, the implementation of a system like PETREE could offer significant advantages for small-scale producers. This academic analysis aims to explore the potential benefits, applicability, and socio-economic implications of such a system within a similar agricultural framework. Additionally, the possibilities of discussing the feasibility of utilizing microfinance to support the adoption of this innovative solution are included. The benefits of a PETREE-Like System for Small Producers in developing countries which based on agriculture economies like Turkey include the following:

- Utilization of Non-Agricultural Idle Lands: A PETREE-inspired system could enable small-scale producers to cultivate crops even on non-agricultural idle lands, thereby expanding their production capacity and enhancing food security.
- Increased Productivity: The system's standardized infrastructure and controlled environment would enhance crop yields, enabling producers to optimize their output even in fragmented and limited land parcels [61].
- Socio-Economic Empowerment: By providing small-scale producers with access to modern technology and sustainable farming practices, a PETREE-like system could contribute to their economic empowerment and resilience in the face of socio-cultural challenges.
- Feasibility and Applicability

Microfinance Utilization: Introducing microfinance schemes tailored to support the adoption of the PETREE-like system among small-scale producers could facilitate access to capital, enabling them to invest in the necessary infrastructure and technology [61,62].

Commercial Viability: From a commercial and economic standpoint, the implementation of a system like PETREE holds promise for scalability and profitability, offering a sustainable and efficient solution for small-scale producers in Turkey.

4.6. Future Steps for Enhanced Viability

Collaboration with Government Initiatives: Partnering with government agencies and agricultural authorities to integrate the PETREE-like system into existing agricultural support programs could enhance its visibility and adoption among small-scale producers.

Research and Development: Continuous research and development efforts to tailor the system to the specific needs and challenges of the Turkish agricultural sector would be crucial for its long-term success and widespread implementation.

Capacity Building and Training: Providing training and capacity-building programs for small-scale producers on the operation and maintenance of the PETREE-like system would be essential to ensure its effective utilization and sustainability.

Market Linkages: Establishing strong market linkages and value chain partnerships for the produce grown using the system could enhance market access and profitability for small-scale producers, making the system economically viable and attractive for investors.

In summary, implementing a system like PETREE in the Turkish agricultural sector shows great potential for solving the problems encountered by small-scale producers in a complex socio-cultural setting. Through utilizing the advantages of this system, employing microfinance techniques, ensuring practicality, and taking proactive measures to improve sustainability and growth, stakeholders, investors, and policymakers can play a part in promoting sustainable growth and economic empowerment of the small-scale producers in Turkey's developing agricultural industry [62].

5. Conclusions

To summarize, the use of plastic in traditional greenhouses has demonstrated favorable outcomes in terms of water preservation, ecological accountability, and economic contributions to the agricultural industry. The internationally awarded PETREE design (Green Dot Gold Award 2010, International Design Award; IDA Rural and Urban Sustainability Bronze Award 2011), (A Design Award 2013–2014) Sustainable Products and Projects in Green Design category Silver Award) characterized by its focus on reusability and sustainable methodologies, offers a valuable option for urban and rural regions alike that aim to foster sustainability and environmental preservation. Although the PETREE system offers advantages for small-scale producers and those working in areas with inadequate infrastructure, it is crucial to assess its suitability for large-scale industrial producers. Future studies should prioritize evaluating the scalability and adaptability of the PETREE system to effectively meet the specific requirements and expectations of large-scale greenhouse operations. In addition, continuous endeavors should also investigate the progress in plastic materials, aiming to create more environmentally friendly options that can decompose naturally or can be manufactured from recycled sources. This would moreover bolster the environmental sustainability of plastic utilization in greenhouses and help to build a more cyclical and conscientious strategy for agriculture.

In conclusion, extensive research and analysis on the use of plastic in agriculture indicate its capacity to enhance water preservation, foster industry collaboration, and stimulate economic development. The PETREE system serves as a successful solution that promotes the practice of reusing and maintaining sustainability. Nevertheless, additional investigation is required to assess its appropriateness for producers on a big scale and to investigate novel plastic materials that adhere to the ideals of global sustainability and environmental stewardship.

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