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Energy Potential of Greenhouse Plant Residue: The Cases of Turkey and Poland

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Abstract

The search for waste management opportunities is crucial for achieving environmentally friendly waste practices and ensuring the country's energy security. This research aimed to valorize biomass and waste generated in greenhouses and to analyze the potential for electricity production from this waste. The analyses compared the situations in Turkey and Poland, where greenhouse production of vegetables is developing and constitutes an important link in agricultural activities, despite differences in climatic conditions. The cultivation of vegetables and flowers under cover is rapidly expanding in both countries and, with changing climatic conditions, is expected to shape the future of agriculture. In addition to estimating the energy that can be obtained, the study also evaluated the economic benefits of such a solution and the volume of avoided CO_2 emissions from fossil fuels. The issue of utilizing these wastes is significant because current methods of their management do not lead to energy production, so their considerable energy potential is wasted, as highlighted in this study. Moreover, there is a lack of similar studies in the literature. The plant species chosen as materials in this study were tomatoes, peppers, eggplant, watermelon, and melon in the case of Turkey. For Poland, the analysis was conducted for tomatoes and greenhouse cucumbers. These crops represent the largest cultivated areas under cover in the respective countries. Results indicated that the average yearly amount of vegetable residue is approximately 463 thousand Mg in Turkey, and 77 thousand Mg in Poland. The estimated annual electricity potential is 430 GWh in Turkey and 80 GWh in Poland. Considering the efficiency of power generation in a typical power plant, the real amount of electricity to be obtained is 0.46 MWh per Mg of waste in Turkey and 0.52 MWh in Poland.

Keywords: agricultural waste; energy; electricity; economic effects; carbon dioxide emissions

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1. Introduction

Considerable amounts of vegetative residue are generated by agricultural activity [1]. Vegetable residues are the parts of a plant that have no commercial value. Appropriate waste management is necessary to prevent environmental and health problems arising from the remaining parts of the plants after production has been completed. Effective waste management is essential for ensuring adequate environmental hygiene in rural areas. Poor management of residues can lead to a wide range of diseases and pests, potentially affecting crops, animals, and humans living nearby [2]. If crops are grown in cycles, additional problems may arise from improper crop residue management. When this cultivation technique is used, the residues can carry pathogens from one cycle to the next, which makes them more difficult to control [3]. With an appropriate regulatory framework that emphasizes and prioritizes the circular management of agricultural waste, there are numerous opportunities to enhance the existing waste management system. Furthermore, the results of economic analyses indicate that self-managing waste biomass, particularly from tomato crops, is a financially viable alternative [4].

Unfortunately, such plant biomass waste is still thrown into the greenhouse environments, seaside areas, stream beds, or landfills, or it is mixed with greenhouse soil after shredding. Combustion of this waste, after it has dried naturally, causes air, environmental, and visual pollution. In addition, pesticide and chemical fertilizer residues in the plant can leach underground with rainfall and pollute water resources. Mixing the waste into the greenhouse soil or throwing it into the greenhouse environment can stimulate the development of tomato moth (Tuta Absoluta) or other diseases, pathogens, and pests, which have threatened tomato cultivation, especially in recent years, as these agents remain in the environment until the next cultivation period. Therefore, the effects of pests are increasing every year. However, it is possible to utilize greenhouse vegetable wastes in other ways, e.g., as solid fuel by briquetting or for the production of biogas and compost [5].

Oleszek et al. [6] and Kulichkova et al. [7] highlight several benefits of waste-to-energy solutions. The conversion of plant residues into biogas provides a renewable alternative to fossil fuels, contributing to energy security and sustainability. Recovery of agricultural residues minimizes waste disposal issues, reducing the environmental burdens and financial cost associated with landfills. The location of biogas facilities near agricultural waste sources can mitigate greenhouse gas emissions and promote better waste management practices, enhancing overall environmental health.

Vatsanidou et al. [8] discuss the benefits of generating electricity from biomass energy obtained from greenhouse plant residues, particularly through the lens of sustainable agricultural practices and life cycle assessment (LCA). They indicate that utilizing greenhouse plant residues for biomass energy helps to manage agricultural waste effectively, reduce the quantity of this waste, and contribute to a circular economy.

Energy consumption is an indicator of countries' levels of development and is indispensable for individuals to live comfortably. However, the increase in energy consumption, alongside developing technology and an increasing population, poses an important global problem. For this reason, the importance of studies on utilizing renewable energy sources has increased in recent years. Biologically derived resources have been one of the primary renewable sources of energy used by humanity since ancient times [9]. In the field of renewable energies, biomass will play a fundamental role in the coming years, especially due to the rise in fossil fuel prices, the questionable safety of nuclear energy, and the need to reduce CO_2 emissions [10]. The need for energy resources in the world continues to increase daily. Energy demand will increase in the coming years, especially in developing countries, in parallel with population growth, industrialization, and technological developments. Fossil energy resources cause environmental problems, and their reserves will be depleted quickly. Dependence on source countries leads to various political and economic issues, and price instability increases interest in renewable energy resources. Therefore, there should be increased emphasis on investments in and development of renewable energy sources, such as hydraulic, wind, geothermal, solar, biomass, wave, and hydrogen [11–13]. As a developing country, Turkey's need for energy resources is increasing daily in parallel with its population and growing economy. Reducing Turkey's dependence on nonrenewable energy sources, which is approximately 75% externally dependent due to its current energy structure, seems to be an obligation rather than a choice [14]. Turkey has the potential to produce a lot of renewable energy but, on the other hand, it also imports a lot of energy. Therefore, to become energy-independent, renewable energy resources must be used more widely. Scientists see great potential in using post-production waste, e.g., from the dairy industry, to generate energy in this country [15]. Moreover, agricultural residues are attractive because they are sustainable, environmentally friendly, and familiar energy sources. In addition, Turkey has many advantages and alternatives in using agricultural residue resources due to its regional climate [12].

Biomass energy is a renewable energy source that is environmentally friendly and does not contribute to air pollution. This makes it an increasingly relevant source of energy worldwide. It offers several advantages over fossil fuels, as it does not contain harmful substances or sulfur. Additionally, biomass is an inexhaustible resource, since plant cultivation can continue as long as solar energy persists. Through various processes, biomass can be converted into heat, electricity, solid fuels, liquid fuels, gaseous fuels, and other products [5,7].

Bioenergy refers to renewable energy derived from biological sources, including living or dead organisms (such as plants and animals) and their by-products. Often, biomass is used as a fuel, especially when derived from plant materials grown for non-food purposes. Common biomass energy sources include forest residues, animal manure, municipal solid waste, and by-products from agro-industrial processing, such as pulp [16–19]. Jiang et al. [20] predict that renewable energy will play a crucial role in electricity generation. To this end, entities such as the European Union, and countries such as the USA, and China are actively working to increase the utilization of product residues in energy production processes.

In studies conducted by researchers to determine the energy potential of greenhouse waste, Tock et al. [21] reported a maximum power of 80.52 MW from direct combustion of banana biomass and 869.13 MW from anaerobic digestion as a potential renewable energy source in Malaysia, corresponding to an overall energy surplus of 949.65 MW. Additionally, as considered in Malaysia's Fifth Fuel Policy (Eighth Malaysia Plan 2001–2005), renewable energy has been declared as the fifth fuel in the energy supply mix, aiming to account for 5% of the country's total energy consumption. Banana biomass energy, which met approximately 4.6% of Malaysia's total capacity in 2007, met more than half of its renewable energy needs. Callejón-Ferre et al. [22] reported that the annual total dry waste amount of tomato, pepper, eggplant, squash, bean, melon, and watermelon plants grown in greenhouses in the Almeria province of Spain has an energy value of over 250 thousand Mg and 3 million GJ year^{-1}. Moreover, it has been determined that the total energy value of greenhouse vegetable biomass waste (tomato, pepper, and eggplant) in Turkey is approximately 3.99 PJ [19]. Karaca [23,24] found that the total calorific value of vegetable biomass residues resulting from the production of tomato, pepper, and eggplant plants grown under cover in Antalya province of Turkey is 3.19 PJ. Boyaci et al. [25] calculated that the biomass residual energy potential resulting from greenhouse tomato production in Kırşehir province of Turkey is 4.05 TJ in total. It can therefore be observed that tomato waste, apart from being used for composting and thus enriching soils with insufficient organic matter content [26], can also be used to generate energy.

Electricity demand from renewable energy facilities has been increasing over the years in EU countries and Turkey. European Union country practices are followed in producing energy efficiency and saving policies, and necessary regulations are included in plans and programs. EU harmonization laws positively affect these resources, as they support environmentally friendly renewable energies [27]. Alternative energy sources can help meet acute energy demand and sustain economic growth in many world regions. Bioenergy is gaining importance in the global fight to prevent climate change. The scope of utilizing organic wastes as an energy source is not limited to the direct combustion of these wastes. Biogas, biofuels, and woody biomass are other energy sources that can be obtained from organic waste materials. These biomass energy sources have a significant potential in combating climate change [28]. Biomass and agricultural waste, as energy resources, have significant potential for Turkey and Poland. In this sense, it is clear that developing biomass-oriented energy policies will significantly help to obtain sustainable, domestic, cheap, and clean energy [29–31].

Studies on greenhouse waste management across various regions in Turkey and Poland have revealed significant challenges in handling vegetable waste in an environmentally sustainable manner. In Antalya province, only 8.7% of vegetable waste is used for composting, while as much as 91.3% is disposed of in ways harmful to the environment: 63.3% is left in fields, 8.7% is dumped into rivers or streams, and 19.3% is left to decompose naturally [24,30]. Similarly, in Denizli province, 12% of enterprises leave pruning waste inside greenhouses, 15% discard it in fields, 37% burn it, and 22% dispose of it in garbage bins [12]. These practices not only harm ecosystems but also contribute to atmospheric pollution. There is a pressing need for the widespread adoption of sustainable waste management practices, such as composting, to mitigate the environmental impact of agricultural waste in Turkey. In Poland, there is currently no detailed record-keeping of the mass and composition of agricultural waste (especially from greenhouses) and their management, which directly arises from the legal regulations concerning biomass and agricultural waste [32,33]. These wastes are most commonly subjected to composting, biological drying, or left in the fields to enrich the soil [34,35]. Additionally, in Poland, it is noted that despite the agricultural and food sector having significant potential for biogas and biomethane production, the current utilization of these resources is surprisingly low [31].

The novelty of this study lies in its focus on greenhouse-derived plant residues and their direct potential for energy recovery, which remains largely overlooked in the current literature [4–6]. Most studies concentrate on agricultural waste in general; they rarely analyze the biomass generated specifically within greenhouse systems. A significant proportion of these residues is either composted, subjected to anaerobic digestion, or, more commonly, discarded through landfilling, leading to irreversible material and energy loss [31]. Given the growing scale of greenhouse horticulture, especially in countries such as Turkey and Poland, there is a need to identify sustainable and economically viable solutions for managing this biomass stream. Addressing this issue not only supports circular economy goals but also contributes to the development of low-emission energy systems in the agricultural sector [4].

This study aims to determine the amount of electrical energy that can be obtained using plant residues generated in greenhouse enterprises in Turkey and Poland. The analysis takes into account the most popular crops grown under cover in both countries. The comparison of the two countries aims to examine the similarities and differences in the energy potential of waste from greenhouse production. Turkey, as one of the leaders in global vegetable production under cover, has a production area under cover that is ten times larger than that of Poland, and it can serve as a model for organizing this type of production. Estimating the energy potential of agricultural waste is crucial for implementing the principles of sustainable development and circular economy in agriculture.

2. Materials and Methods

2.1. Materials

The area and production amounts of greenhouses were considered over 10 years, from 2013 to 2022, and input data were derived from statistical office databases in Turkey (TUIK) and Poland (GUS) [36–38]. Considering greenhouse production in the two analyzed countries, slightly different plants were included in each country. To calculate the potential energy that could be obtained from plant residues in the research area, the annual data were analyzed first.

This research includes residues from tomato, pepper, eggplant, cucumber, watermelon, and melon plants grown in greenhouses as plant material in Turkey. Since Turkey is one of the world's most important greenhouse-growing centers, it generates a large amount of vegetable residue at the end of the annual harvest. The idea that Turkey's ever-increasing energy costs and needs can be met from this large surplus emphasizes its importance in reducing negative effects on the environment and the economy.

For Poland, the analysis was limited to tomatoes and cucumbers, since, according to the data, these vegetables are most often grown under cover [39]. In the cultivation of vegetables under cover, tomatoes account for 57% of production, and cucumbers for 31%. It was assumed that, in Poland, the crop residue from tomato cultivation would be used for direct combustion or would produce biogas, which could be used for electricity generation.

2.2. Methods

This part of the study involved making calculations regarding the amount of residues produced by selected plants grown in greenhouses, the energy potential obtainable from these residues, and the conversion of this energy. This section explains the conversion of the energy potential into different energy sources, the potential reduction in carbon dioxide emissions from residues, and the economic benefits of using residues for energy production.

2.2.1. Amount of Product Residual

In determining the energy potential obtained from greenhouse vegetable residues, the total residue amounts were determined with the help of the fresh and dry weight of residue per hectare, the cultivation area, and the usability rate (Equation (1)).

$$TAR = ADR \cdot CA \cdot UR \text{ [Mg]} \tag{1}$$

where

TAR—total mass of residues (Mg);

ADR—amount of dry residue ($Mg \cdot ha^{-1}$);

CA—cultivated area (ha);

UR—usability rate (%).

The values determined by the researchers were used to calculate the plants' fresh and dry biomass residue amounts [6,15,20,23,35,39]. Since all greenhouse residues can be removed and collected from their location, the usability rate of greenhouse residues is accepted as 100% [16,22,40]. In the case of biogas production, the analysis of its yield was developed based on the literature [2,7,30,31] and the authors' own studies. The residual mass takes into account both the waste generated during crop decommissioning and from cultivation treatments.

Greenhouse cultivation constitutes a crucial part of agricultural production in Turkey. As of 2022, greenhouses are built on an area of approximately 81 088.2 hectares, producing 8.2 mln Mg of crops. In Turkey, tomato cultivation occupies the largest share of the total greenhouse area (32%) and total production (50.6%). Species belonging to the *Solanaceous* family (tomatoes, peppers, and eggplants) constitute approximately 60% of the products grown in greenhouses. The area of greenhouse cultivation in Poland is significantly smaller (Table 1), although it is characterized by greater planning efficiency [6,31].

Table 1. Average amount of residues from greenhouses based on wet and dry weight.

Plant Species	Production Area (ha)	Biomass Fresh Weight ($Mg\cdot ha^{-1}$)	Biomass Dry Weight ($Mg\cdot ha^{-1}$)	References
		Turkey		
Tomatoes	25,829.7	73.2	10.5	[8]
Pepper	8150.9	54.0	9.3	[8]
Eggplant	3240.3	54.2	9.0	[8]
Watermelon	1085.7	24.0	4.8	[22]
Melon	3526.5	33.0	6.6	[22]
		Poland		
Tomatoes	1295.0	171.43	25.5	own study
Cucumbers	771.0	41.2	4.5	own study

2.2.2. Calculating the Amount of Energy That Can Be Obtained from Plant Residues

Potential total energy values were calculated using the high heating value determined for the residue amounts (Table 2) [15,19,41,42]. We assumed in the calculation a moisture content of residue at an average level of 50% and a heat of evaporation equal to 2.25 $MJ\cdot kg^{-1}$ [5,6,11].

Table 2. Ash content and high heating values of waste from cultivation.

Plant Species	Ash Content (% d.m.)	High Heating Value on Dry Basis ($MJ\ kg^{-1}$)	References
		Turkey	
Tomatoes	7.67	15.36	[5,27]
Pepper	3.67	17.51	[5]
Eggplant	4.33	17.38	[5]
Watermelon	20.58	14.26	[11,13]
Melon	28.38	13.50	[11,13]
		Poland	
Tomatoes	3.14	17.56	[6]
Cucumber	2.98	16.62	own studies

2.2.3. Converting the Energy That Can Be Obtained from Plant Residue into Electricity

There may be significant variations in the efficiency of electrical generation from biomass, depending on the scale of installation and the technology used (biomass-only or co-firing with coal). According to the literature, the efficiency factor for biomass-to-energy conversion ranges between 10 and 40% [43], with the most commonly assumed value being 25% [44]. Therefore, in our calculations, we assumed an efficiency of 25%.

2.2.4. Number of Houses Whose Electricity Needs Are Met

The number of houses that could be supplied with electricity if the available electricity generation capacity were used was calculated by dividing the average electricity consumption of a house by the amount of electricity that can be generated.

2.2.5. CO_2 Emissions (Carbon Footprint)

The average greenhouse gas emission for producing 1 kWh of electricity in Europe by combustion of coal is 1.023 kg CO_2 kWh^{-1}; for natural gas, it is 0.434 kg CO_2 kWh^{-1}; and the amount of CO_2 released by biomass into the atmosphere is 0.025 kg CO_2 kWh^{-1} [6,39,44,45]. In Turkey, 34.6% of electricity production comes from coal and 22.9% from natural gas [46]. This makes the energy sector an important polluter. Emission values released from coal and natural gas were calculated, since they provide the majority of electricity production in Turkey (57.5%).

2.2.6. Economic Effects Gain from Electricity Production

The unit price of electricity for medium-sized households varies from year to year. Economic gains can be achieved by calculating the amount of electricity used by medium-sized households. This is calculated by multiplying the unit price by the amount of electricity used in kWh.

3. Results and Discussion

The changes in the area and production amounts of plants grown in greenhouses in Turkey (tomatoes, peppers, eggplants, watermelons, and melons) and Poland (tomatoes and cucumbers) are shown in Figure 1.

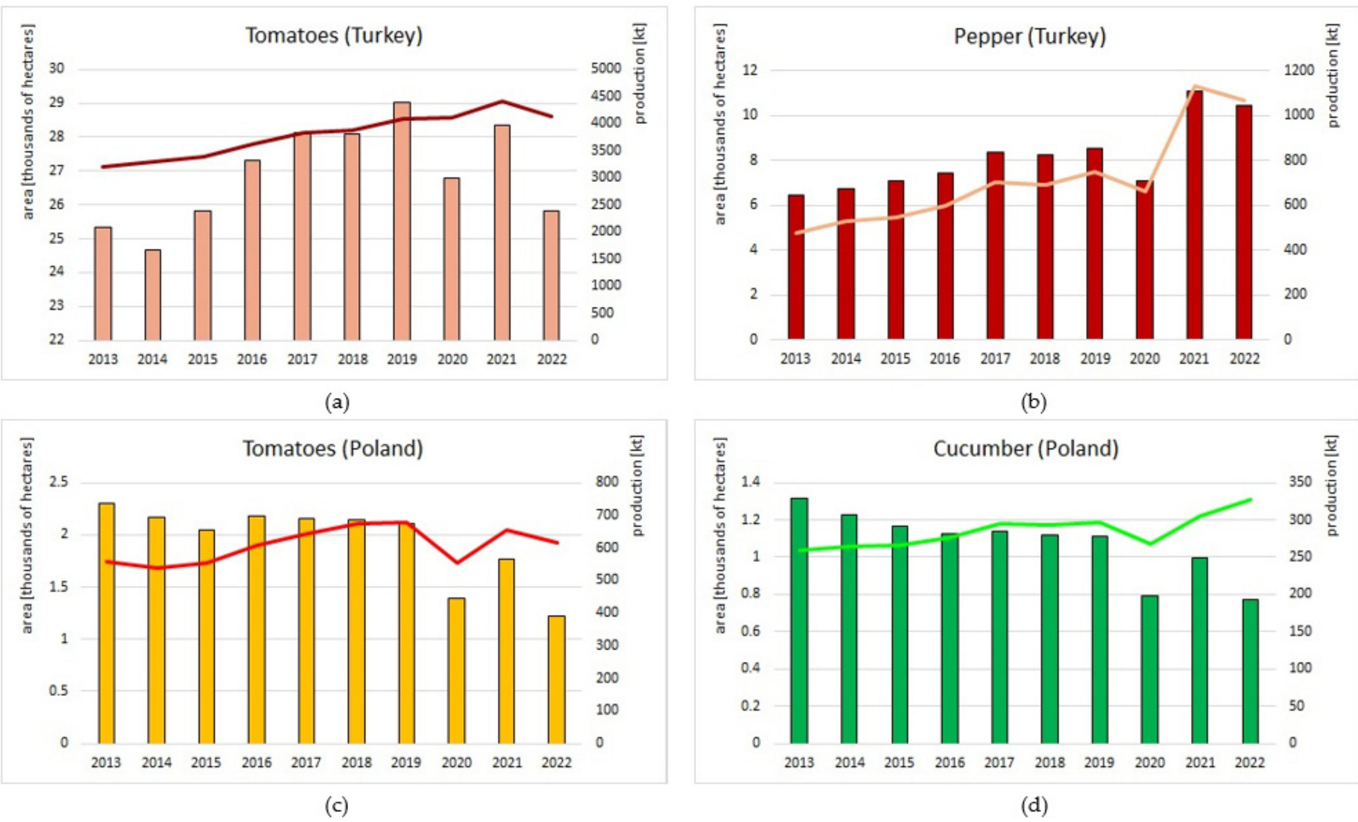
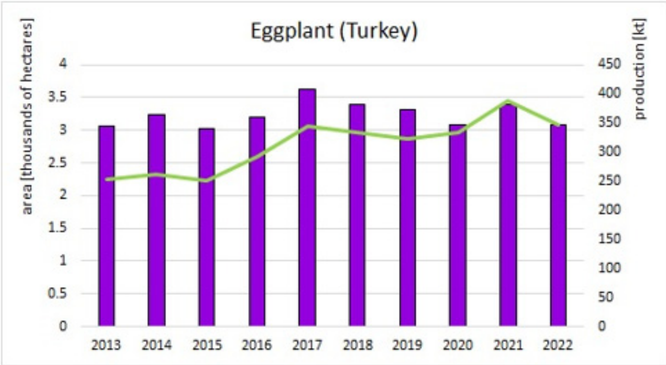


Figure 1. *Cont.*



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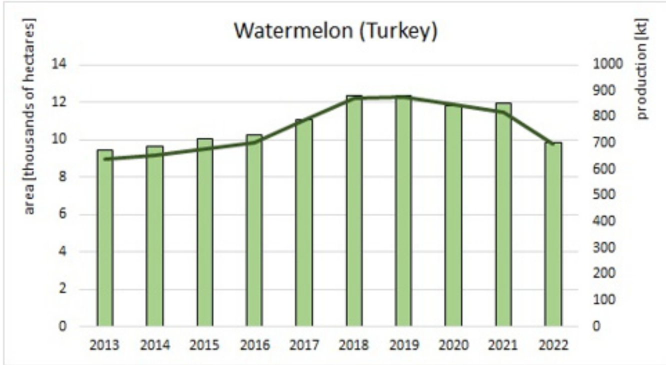

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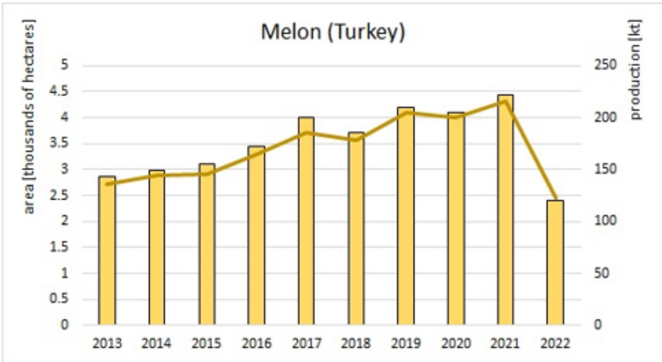

(g)

Figure 1. Change in area (bars) and production (line) of selected crops grown in greenhouses between 2013 and 2022: (**a**) tomatoes in Turkey, (**b**) pepper in Turkey, (**c**) tomatoes in Poland, (**d**) cucumber in Poland, (**e**) Eggplant in Turkey, (**f**) watermelon in Turkey, (**g**) melon in Turkey.

According to Figure 1, the average yield per hectare (±standard deviation) in Turkey is 140.8 ± 11.5 Mg ha^{-1} of tomato, 86.5 ± 9.9 Mg ha^{-1} of pepper, 96.4 ± 12.4 Mg ha^{-1} of eggplant, 69.7 ± 1.7 Mg ha^{-1} of watermelon, and 48.2 ± 1.3 Mg ha^{-1} of melon. In Poland, the average yield for greenhouse tomatoes is higher and amounts to 312.4 ± 80.7 Mg ha^{-1}, and for cucumbers 264.9 ± 67.0 Mg ha^{-1}. Although climatic conditions in Turkey and Poland differ, particularly in terms of temperature and day length, these differences do not appear to have a significant impact on crop yields, as greenhouse production is conducted entirely under controlled conditions. In Turkey, the warmer climate and longer photoperiods may favor plant growth, but in Poland, such differences are effectively mitigated by the use of supplementary lighting during the winter season. In Poland, numerous scientific studies are being conducted to enhance crop yields, particularly within the context of optimizing greenhouse production processes, which constitutes a growing area of research with both scientific and practical significance.

The amount of residue (calculated on a dry weight basis) that can be produced as a result of greenhouse farming activities in Turkey and Poland is given in Tables 3 and 4.

The total potential amount of electricity produced from plant residue energy and each country's electricity consumption values are given in Tables 5 and 6.

Biomass differs from other alternative energy sources due to its resource diversity and the variety of conversion processes available [47]. It was determined that the energy that can be obtained by utilizing vegetable residues in Turkey is 429.8 GWh per year. Based on Turkey's electricity consumption over the past 10 years, an average of 0.18% can be met from greenhouse residues (tomatoes, peppers, eggplants, watermelons, and melons). In Poland, the energy potential is calculated as 80.2 GWh per year, which covers less than 0.1% of energy demand. The relatively low proportion of energy that can be obtained from plant residues is due to both the high electricity usage and the limited scope of crops considered in this study. If additional agricultural and animal residues were included, the total energy yield would increase, raising the coverage rate. A comparison of energy obtained and waste generated shows that an average of 0.46 MWh of potential electricity can be obtained annually from 1 Mg of greenhouse residues in Turkey, and 0.52 MWh in Poland. According to Niemiec et al. [31], in Poland, the residues from tomatoes and cucumbers under cover (as indicated in Table 4), if used for biogas production, can yield 4964.2 GWh of heat per year. Based on the cultivation area of these crops, this could cover 50% of the heat demand of greenhouse facilities.

Table 3. Amount of vegetable residue (dry weight) in Turkey.

Year	Tomatoes (Mg)	Pepper (Mg)	Eggplant (Mg)	Watermelon (Mg)	Melon (Mg)	Total (Mg)
2013	265,747.4	59,941.4	27,620.7	45,327.8	18,949.9	417,587.2
2014	258,587.9	62,371.8	29,239.0	46,135.7	19,659.4	415,993.8
2015	270,674.5	65,675.5	27,315.9	48,072.5	20,511.5	432,249.9
2016	286,616.2	69,255.7	28,912.5	49,016.2	22,770.0	456,570.5
2017	295,268.3	77,883.3	32,849.1	53,018.9	26,471.3	485,490.9
2018	294,564.4	76,499.7	30,742.4	59,100.0	24,447.7	485,354.2
2019	304,478.5	79,017.3	30,041.3	59,168.2	27,758.3	500,463.7
2020	281,030.2	65,604.0	27,832.4	56,570.9	27,037.6	458,075.1
2021	297,584.5	103,110.1	30,741.5	57,392.2	29,225.5	518,053.7
2022	270,953.6	97,045.6	27,805.3	47,334.2	15,915.2	459,053.9
Average	282,550.5	75,640.4	29,310.0	52,113.6	23,274.6	462,889.3

Table 4. Amount of vegetable residue (dry weight) in Poland.

Year	Tomatoes (Mg)	Cucumber (Mg)	Total (Mg)
2013	58,675.3	33,587.3	92,262.6
2014	55,357.4	31,342.8	86,700.2
2015	52,185.5	29,810.8	81,996.3
2016	55,578.8	28,759.9	84,338.7
2017	54,832.4	29,058.5	83,890.9
2018	54,589.1	28,442.4	83,031.5
2019	53,617.3	28,324.6	81,941.9
2020	35,385.8	20,266.9	55,652.7
2021	44,981.2	25,451.0	70,432.2
2022	31,087.1	19,656.4	50,743.5
Average	49,629.0	27,470.1	77,099.1

It was determined that greenhouse residues have a significant energy potential, which is extremely important for the electricity system of the analyzed countries, which heavily depend on foreign energy sources. Similar conclusions were reported in works by Tock et al. [21], Callejón-Ferre et al. [22], Karaca [23], Atılgan et al. [30], and Boyacı et al. [26]. So far, few countries have effectively developed crop residues for energy purposes. One such country is Ukraine, which annually generates up to 128.47 million Mg of agricultural crop residues. Of these, 48.66 million Mg may be used for energy production [20].

In general, when greenhouse waste is used for energy purposes, it is most commonly directed toward biogas production. According to the European Biogas Association's 2023 database, the agricultural sector plays a significant role in Europe's biogas and biomethane production, with 67% of biogas and 64% of biomethane originating from agricultural plants.

This highlights the substantial contribution of agricultural feedstocks such as manure, sequential crops, and other residues [48].

Table 5. Energy (MWh) obtainable from vegetable residues and consumed in Turkey.

Year	Tomatoes (MWh)	Pepper (MWh)	Eggplant (MWh)	Watermelon (MWh)	Melon (MWh)	Potential Energy Amount (MWh)	Electricity Consumption in Turkey (GWh)
2013	241,941	63,521	29,021	37,805	14,805	387,092	198,045
2014	235,423	66,097	30,721	38,478	15,359	386,078	207,375
2015	246,427	69,598	28,701	40,094	16,025	400,843	217,313
2016	260,940	73,392	30,378	40,881	17,789	423,380	231,204
2017	268,817	82,535	34,514	44,219	20,681	450,766	249,022
2018	268,176	81,068	32,301	49,291	19,100	449,936	258,232
2019	277,202	83,736	31,564	49,348	21,686	463,537	257,273
2020	255,855	69,522	29,243	47,182	21,123	422,925	262,702
2021	270,926	109,268	32,300	47,867	22,832	483,193	286,691
2022	246,681	102,841	29,215	39,478	12,434	430,649	284,841
Average	257,239	80,158	30,796	43,464	18,183	429,840	245,270

Table 6. Energy (MWh) obtainable from vegetable residues and consumed in Poland.

Year	Tomatoes (MWh)	Cucumbers (MWh)	Potential Energy Amount (MWh)	Electricity Consumption in Poland (GWh)
2013	62,383	33,517	95,901	149,789
2014	58,856	31,278	90,133	150,974
2015	55,483	29,749	85,232	150,312
2016	59,091	28,700	87,791	156,161
2017	58,298	28,998	87,295	159,024
2018	58,039	28,383	86,422	162,924
2019	57,006	28,266	85,271	160,977
2020	37,622	20,225	57,847	157,086
2021	47,824	25,398	73,222	163,997
2022	33,052	19,615	52,667	163,455
Average	52,765	27,413	80,178	157,470

In the Czech Republic, the company AGROECO, based in Ostrava, is developing solutions focused on accelerating the biological drying process of agricultural waste, including greenhouse residues [49], prior to their gasification for energy purposes (syngas production). This approach is particularly important due to its circular nature. Waste used for biogas production generates large volumes of digestate, which can be applied as fertilizer; however, due to the quantity produced, its management may be problematic (e.g., finding a sufficient number of farmers willing to use it). In contrast, the direct combustion of greenhouse waste generates only small amounts of solid residue, which can also be used for environmental purposes—thus contributing to the closure of nutrient cycles in the ecosystem. Pilot studies on the combustion of greenhouse residues for energy production, including residues from tomato cultivation, were conducted in Almeria Province, Spain, an area known for its extensive tomato greenhouse industry [50]. Also in Turkey, research was carried out on the development of a prototype machine intended for producing bio-briquettes from greenhouse waste generated by high-value vegetable crops such as tomatoes, eggplants, and peppers. The findings from the conducted tests confirmed that the briquetted biomass produced with the prototype displayed very good properties, making it a viable option as a solid biofuel [51].

In calculating economic benefits, it is important to remember that the unit price of electricity for medium-sized households varies annually [52,53]. The economic gains that can be achieved if the electricity generated is used by medium-sized households are shown in Table 7.

Table 7. Economic effects from electricity use by medium-sized households (EUR·year^{-1}).

Country	Obtainable Electricity (MWh)	Unit Price * (EUR·MWh^{-1})	Total Economic Gain (EUR)	Households with Covered Electricity Needs (Number)
Turkey	429,840	110.7	47,583,288	186,887
Poland	80,178	53.0	4,249,439	32,071

* The unit price of electricity for medium-sized households.

The average electricity consumption of a household is 2.3 MWh·year^{-1} in Turkey and 2.5 MWh·year^{-1} in Poland [45,54,55]. According to Table 7, the average annual economic gain from energy obtained from greenhouse waste is EUR 47.58 million in Turkey and EUR 4.25 million in Poland. Moreover, it is assumed that the highest number of households that could meet their electricity needs from this energy is nearly 187,000 in Turkey and over 32,000 in Poland.

Biomass-based renewable energy resources currently have limited application, both globally and in the analyzed countries, due to technological and economic challenges. Biomass can meet various energy needs, including electricity generation, heating, vehicle refueling, and process heat for industrial facilities [56]. Thus, using energy obtained from vegetable residues to meet household electricity needs can be advantageous both economically and in terms of expanding access to renewable energy.

Data comparing CO_2 emissions from fossil fuels required to produce the same amount of energy as generated in this study are shown in Table 8.

Table 8. CO_2 emissions released into the atmosphere by fuels.

Country	Obtainable Electricity (MWh)	Natural Gas (Mg CO_2eq)	Coal (Mg CO_2eq)
Turkey	429,840	186,551	439,726
Poland	80,178	34,797	82,022

Although the share of fossil fuels in global energy use has decreased significantly over the past 50 years, they still supply 80% of total energy demand [57]. Fossil energy sources have a high potential for environmental pollution [10,58]. In Turkey, 35% of electricity production comes from coal and 23% from natural gas [19]; in Poland, it is 61% from coal and 10% from natural gas [59]. The amount of CO_2 emissions into the atmosphere can be significantly reduced if the plant residues described in this study are used to generate electricity. As indicated in Table 8, more than 186,000 Mg of CO_2 could be avoided in Turkey compared to the use of natural gas, and more than 439,000 Mg of CO_2 compared to coal. In the case of Poland, these values are lower due to the smaller electricity yield from this waste (Table 8).

Karaca [23,24] reported that replacing the entire energy value of greenhouse biomass residues with coal would release 265,800 Mg of CO_2, while using the residues instead would reduce emissions to 22,150 Mg. Boyacı et al. [26] found that replacing the entire energy value of biomass residue energy (4 046 208 MJ) that can be obtained from greenhouse residues with coal or natural gas would result in annual CO_2 emissions of 337 Mg and 213 Mg, respectively, and that this amount could be reduced to 28 Mg by using the residues. As a result of the calculations made in this study, the fact that biomass not only produces energy but also releases less CO_2 into the atmosphere than many fossil fuels is critical for reducing the amount of greenhouse gas emissions. Thus, preventing CO_2 emissions resulting from electricity production using plant residues will also reduce the impact of global warming. Therefore, the use of plant residues in energy production has economic and environmental advantages.

Nguyen and Matsui [60], in research on household solid waste management, support the notion that managing agricultural plant waste can be beneficial, particularly when considering economic viability, environmental impacts, and the potential for recycling and energy generation. The integrated approach presented in this study can help stakeholders make informed decisions about waste management practices in agriculture. Danevad and Carlos-Pinedo [61] support the notion that managing plant residues from agriculture through anaerobic digestion not only contributes to sustainability and environmental protection but also presents economic opportunities, making it a worthwhile investment for greenhouse operations. Greenhouse vegetable production uses large amounts of energy and other resources, so finding ways to reduce its environmental impact could increase its sustainability. Szyba and Mikulik [62] illustrate that utilizing agricultural plant waste for energy production is economically viable and environmentally beneficial, aligning with the goals of sustainability and resource efficiency. This supports the argument that managing agricultural waste through biogas production is a worthwhile investment.

Buko et al. [58] provide specific insights into Poland's energy challenges and reliance on fossil fuels. The results of these considerations indicate that Poland has not irretrievably lost its ability to restore food self-sufficiency in the event of losing access to external sources of fossil fuels. Further studies and data on specific biomass energy potentials from various plant residues in Poland would provide a clearer picture. In countries with industrialized agriculture, the amount of energy provided to society in food is equal to or greater than the amount of energy contributed by fossil fuels. Poland is one such country, lacking sufficient domestic oil and gas resources and therefore dependent on imports of these fossil fuels to benefit from modern solutions in food production and distribution. A prolonged shortage of energy from such sources would pose a serious threat to food security. The potential for biomass energy from agricultural residues presents a viable opportunity for enhancing energy security and sustainability in the country.

Another approach presented in the study by Trypolska [63] highlights the significant biomass potential from agricultural residues, the economic benefits of utilizing this biomass for energy production, and the potential for job creation, reinforcing the idea that managing plant residues can lead to substantial energy and economic advantages. Poland has significant biomass potential, the majority of which comes from agricultural crop waste, corn, and dedicated energy crops. The employment factor method was used to estimate the number of jobs in the bioenergy sector in Poland. The main result of the work is that the number of jobs in agriculture for producing energy feedstock may reach 33,000 by 2030. The production of agri-biomass crops for energy purposes in Poland is supported by the EU's Common Agricultural Policy. Producers of energy from biomass have priority access to the grid and qualify for feed-in tariffs, premiums, auctions, and special financial programs. Despite the benefits of biomass, insufficient installed capacity exists for its utilization due to existing barriers.

4. Conclusions

Turkey, as one of the important greenhouse farming centers of the world, has a high potential in terms of vegetable residues. Poland, with significantly less production volume under cover, also has unused energy potential from agricultural waste. As indicated in this research, obtaining energy from plant residues has many advantages. The most important of these is the electricity production potential. Based on conducted research, it was found that:

- The average yearly amount of vegetable residue is calculated as 463 thousand Mg in Turkey and 77 thousand Mg in Poland;
- The yearly average potential energy that could be obtained in Turkey is close to 430 GWh, while in Poland the potential is 80 GWh;
- The obtained amount of energy can cover approximately 0.18% of the country's electricity demand in Turkey and less than 0.1% in Poland; however, nearly 187 thousand residences in Turkey and over 32 thousand Polish households can be supplied with this source of renewable energy;
- Total economic gain from this potential electricity is estimated as EUR 47.58 million in Turkey and EUR 4.25 million in Poland, which is conditional and depends on many macroeconomic variables;
- Taking into account the efficiency of the power generation process in a typical power plant, the real amount of electricity to be obtained is 0.46 MWh per Mg of waste in Turkey and 0.52 MWh in Poland;
- In addition to the economic advantages, it is noteworthy that energy obtained from biomass and organic waste from greenhouses can prevent CO_2 emissions related to the combustion of fossil fuels (coal and natural gas);
- It was found out that the amount of avoided CO_2 emissions is over 186 thousand Mg of CO_2 in the case of natural gas and over 439 thousand Mg CO_2 in case of coal in Turkey; in comparison, these values in Poland amount over 34 thousand Mg CO_2 and 82 thousand Mg, respectively.

Due to population growth, energy needs are increasing daily. Providing energy needs from renewable, environmentally friendly sources instead of fossil fuels is important for both economic stability and environmental protection. In this context, utilizing biomass technology to meet energy demands is an attractive option. However, harnessing residues and implementing biomass technology nationwide can be costly and time-consuming. In the future, the authors plan to conduct research on using this waste for biogas production, as it may offer greater economic benefits through the processing of greenhouse residues.

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