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Research Article

Investigation of the potential of greenhouse post-harvest wastes for bioenergy production and utilization for heating and carbon dioxide application

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ABSTRACT

In this study, raw biomass feedstock characterization of greenhouse post-harvest residues of tomato, pepper, and eggplant has been investigated using the wastes of stem and leaves as a source of energy gained from palletization. The characterization was compared to both sawdust and the relevant ISO and EU pellet standards. The proximate and ultimate analyses results of all the tested feedstock materials have proven to be successful candidates for pelletizing and combustion process. The bulk density of tomato, pepper, and eggplant pellets were found to be 568 kg/m^3, 575 kg/m^3, 589 kg/m^3, respectively, and the higher heating values of these produces were found to be 17.25 MJ/kg, 17.45 MJ/kg, and 17.80 MJ/kg, respectively. Based on the results, it is possible to generate 10 tons of waste per hectare capable of producing almost 50 MWh of heating energy. Furthermore, this waste could generate more than 6.5 tons of CO_2 per hectare. The study results suggest that the heating energy potential and the amount of CO_2 emitted could be used in greenhouses to support photosynthesis during low temperature and low solar radiation periods.

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INTRODUCTION

In recent years, the replacement of fossil fuels with environmentally friendly alternative fuels has been intensively studied. There are several reasons to replace fossil fuels with renewable energy resources: increasing oil prices, efforts to reduce carbon dioxide (CO_2) emissions to mitigate global warming, need for sustainable waste management, and collectively adopting a circular economy perspective for all production activities. In this context, biomass could offer clean, renewable energy resource in solid, liquid, and gaseous fuels by valorizing various biomass wastes, including crop harvest residues [1–3].

Limited land resources and agricultural input material pose a risk for increasing food shortages and are currently critical factors that hinder the agriculture sector from achieving global food security goals [4]. In this regard, greenhouse production systems have brought pivotal technologies enabling the implementation of highly productive agricultural systems. On the other hand, intensive farming generates an immense amount of harvest residue that needs sustainable management, every year [5]. It is estimated that the greenhouse vegetable production generates 253,000 tons of harvest residue in Türkiye, annually and most of this residue is either landfilled or incinerated without beneficial use [6].

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One approach to utilizing these wastes could be applied to produce pellet biofuel for space heating in greenhouses, as greenhouse production systems demand heat and CO_2, especially in soilless cultures.

In greenhouse production, producer needs more energy for heating during the cold season, as well as excess CO_2 to support photosynthesis. The countries that experience the four seasons usually need heating for most of the year. For example, the annual greenhouse energy demand in Northern European countries (e.g., Netherlands, Germany, Poland) reaches 3,600 megajoule per square meter (MJ/m^2) [7], while it remains in the range of 220–320 MJ/m^2 in the Mediterranean region. Similarly, the average heat consumption of the Mediterranean region has been estimated to be 200 kilowatt-hour per hectare per hour (kWh/ha.hr), while 500 kWh/ha.hr in Netherlands [8]. Moreover, the average demand of greenhouses for CO_2 has been estimated to be 2,628 t ha−1, annually [8].

For this purpose, greenhouses must be equipped with gas installations metering CO_2 in a pure form or obtaining it by combusting liquefied petroleum gas. In soilless cultures, the enrichment of greenhouses with external CO_2 is generally necessary during cold and low solar radiation. Pellet fuel production from crop harvest residue and combustion thereof could provide a solution for the sustainable management of greenhouse wastes and satisfy the need for energy and CO_2 [7].

Biomass fuel is considered carbon-neutral, locally available, processes modern fuels, and lead to increased employment. A key advantage of harvesting residue products is that their manufacturing processes are fundamentally based on organic waste valorization, aligning with the circular economy concept [9, 10]. Depending on the nature of the feedstock, a diversity of techniques can be used, such as thermal conversion, anaerobic digestion, and solid-state fermentation. Fabricating densified pellets is justified as a simple and well-known technology and can be easily adaptable to the greenhouse that uses solid fuel for heating purposes.

The greenhouse vegetable production industry is one of the agriculture sectors that generate large amounts of post-harvest residue, a potential feedstock for pellet fuel preparation. Tomato, pepper, and eggplant represent the majority of the vegetable crops grown through greenhouse production, worldwide [11]. The cover-crop industry generates wastes of various plants during both the harvesting of crops and post-harvest, and thus, extensively contribute to environmental pollution.

The low density of these biomass resources is a significant limitation for efficient handling, transportation, and possible valorization methods. Pelletizing these biomasses by applying pressure can increase the bulk density by 4 to 5 times [12]. The densified biomass provides a definite size and shapes with higher individual pellet and bulk densities. This, in turn, helps improve the handling and transportation, thereby enabling the possible valorization of the biomass through direct combustion for greenhouse heating. In addition, as densified biomass has a lower moisture content, it could also be stored for longer times with the minimum loss of quality.

Sustainable management of greenhouse residues was subject of many studies in recent decades. Several disposal alternatives such as composting, anaerobic digestion for biogas production, and torrefaction to improve energetic properties have been suggested. There are a few studies in the literature investigating the use of greenhouse harvest residues as pellet fuel materials for the potential of their sustainable and effective use. Due to the increasing demand for alternative fuel sources in recent years, pellet production facilities experienced the supply shortages of raw materials. For this reason, both research institutions and industrial organizations have turned to search for alternative raw materials that can replace wood pellets.

The use of agricultural residues as raw materials for pellets is regarded as one of the alternative solutions to increase the security of raw material supply given the increasing demand triggered by the growth in the pellet industry worldwide, increasing investment in renewable energy, and continuing raw material supply risk [10]. In addition, valorizing greenhouse post-harvest residues as pellet fuel has the potential to contribute to the establishment of small- and medium-sized agro-energy chains [6].

To that end, this study aims to pelletize post-harvest residues of greenhouse vegetables, i.e. tomato, pepper, and eggplant stalks, which are not currently used as biofuel, and determine the pellet fuel characteristics compared to the well-known sawdust pellet. The obtained pellets were evaluated for compliance with the relevant standards compiled by International Standards Organization (ISO) such as ISO 9831:2005 and ISO 18122:2016, and European Union (EU) EN ISO 18847:2016 [13, 14] pellet physical properties of sawdust.

MATERIALS AND METHODS

The post-harvest residues from tomato, pepper, and eggplant crops, which were cultivated in and harvested from a greenhouse in Sakarya, Türkiye, have been investigated in this study. The stalks of tomato, pepper, and eggplant were collected from the greenhouse after the harvest seasons were completed. These crop residues were then dried in the greenhouse for seven days. The vegetable crops were grown, with the density of 3.0 plants per m^2 from April 2020 to November 2020. The air-dried residue samples, with 9–11% moisture content, were ground to the particle size less than 4 mm sieve hole diameters using an industrial scale grinder. Afterwards, biomass pellets were manufactured using an industrial scale pellet mill currently used at biomass

Table 1. Proximate and ultimate analyses of the raw material samples

Parameter	Tomato stalks	Pepper stalks	Eggplant stalks	Sawdust
Proximate analysis				
Volatile matter (%)	62.39	63.88	66.90	67.44
Ash (%)	17.73	16.86	11.82	8.26
Moisture (%)	10.23	9.78	11.12	13.05
Fixed carbon (%)	9.65	9.48	10.16	11.25
Ultimate analysis				
C (%)	38.86	38.25	40.29	47.64
H (%)	5.34	5.77	6.83	6.03
N (%)	0.94	1.14	0.52	0.05
S (%)	0.21	0.42	0.09	0.02
O (%)	54.65	54.42	52.27	46.26

combustion plant for biomass pelleting. Pellet mill parameters were set at a pellet diameter of 10 mm. Samples were continuously fed into a pellet mill through a rotating die-hole press. Approximately 100 kg of samples at equilibrium moisture content were compressed for each experimental trial with a predefined procedure.

Proximate and Elemental Analyses

The dried and ground biomass samples were subjected to physical and chemical analyses to determine the basic chemical parameters, energy potential, and elemental composition. The contents of moisture content, volatile matter, fixed carbon, and ash were measured as proximate analysis parameters. The moisture content was determined on a wet weight basis after drying at the constant weight at 100 °C in a drying cabinet. The volatile matter and ash content were determined by the mass change at 900 °C in a capped crucible and at 550 °C in an open crucible, respectively. The fixed carbon content was estimated by subtracting the mass of the moisture content, volatile matter, and ash from the total mass.

The analyses results provided the percent weights of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) contents of the biomass samples. C, H, and O are the most important components of biomass. C and H are exothermically oxidized to CO_2 and H_2O and contribute positively to the biomass higher heating value (HHV). On the contrary, O contributes negatively to the calorific value. N and S generate gaseous NOx and SO_2 emissions during the combustion of biomass, hence are not desired nor required in biomass fuel. According to the test method, the elemental analysis was carried out using a Leco CHNS-932 elemental analyzer, which enables the simultaneous determination of the C, H, N, and S contents of the raw material samples. O was determined by difference as in Eq. 1.

$$O=100-(C+H+N+S) \quad (1)$$

The calorific value of the samples was determined by using a bomb calorimeter IKA, type C 200 manufactured in Germany. The obtained results represented the HHV (MJ/kg), while lower heating value (LHV) (MJ/kg) was estimated based on the moisture and hydrogen contents of the samples using the following Eq. 2.

$$LHV=HHV-24.42\times(Mc+8.94\times H) \quad (2)$$

In Eq. 2, the coefficient of water in the sample at 25°C (MJ/kg) was assumed to be 24.42; Mc denotes the moisture content in the sample; the coefficient of the hydrogen to water conversion was assumed to be 8.94; and H denotes the hydrogen content in sample (%).

Particle and Bulk Densities

The densities of pellets were determined by measuring the dimensions and weights of the pellet samples. The calculated density is represented by the average of 10 measurements. The bulk density of pellets was determined by filling a known volume container and taking the ratio of measured mass of sample in the container to the volume of the container.

RESULTS AND DISCUSSION

Proximate and Ultimate Analyses

The results of the proximate and ultimate analyses on the harvest residues of raw greenhouse crops and those of the sawdust are given in Table 1. As expected, the volatile matter, ash and fixed carbon contents of the harvest residues of tomato, pepper and eggplant were significantly different from and were lower compared to those of sawdust. In general, a low level of moisture content is required for biomass palletization, as higher levels of Mc cause serious complications during the pressure application and in the final quality of pellet products. The equilibrium Mc is desired to be around 10% for both densification process and pellet storing, handling, and combustion applications. The

Table 2. Pellet quality parameters of tomatoes, pepper, and eggplant, and comparison with sawdust pellet, ISO and EU pellet quality criteria

Parameter	Tomato stalks	Pepper stalks	Eggplant stalks	Sawdust	ISO	EU
Diameter (mm)	10	10	10	10	6–8±1	6–8±1
Length (mm)	14–30	13–32	13–31	13–35	3.15≤ L ≤40	3.15≤ L ≤40
Moisture (%)	11.50	10.20	10.39	12.97	≤10	≤10
Ash (%)	17.64	15.85	12.82	18.90	≤5.0	≤3.0
Bulk density (kg/m^3)	568	575	589	693	≥600	≥600
LHV (MJ/kg)	15.87	16.04	16.16	16.08	≥16.5	16.3–19.0
HHV (MJ/kg)	17.25	17.45	17.80	18.30	–	–
Powder (%)	4.4	3.75	3.60	2.1	≤7.0	≤7.0
Pellet unit density (kg/m^3)	993	1008	985	1080	–	–

high feedstock moisture content (i.e., Mc > 15%) means an unsuccessful densification process. The Mc of the investigated samples was in the range of 9.78% for pepper stalks to 11.12% for eggplant stalks and was lower than those of sawdust (Table 1), which represents a satisfactory Mc range.

Ash content is another parameter determining the fuel quality of the pellets. The ash content was in the range of 11.82% for eggplant stalks to 17.73% for tomato stalks, which were in alignment with the range reported in the literature [5]. Low level of ash content is required for pellet fuel due to the negative impact of high ash content on combustion efficiency, low burning rate, and HHV [3]. The relevant ISO and EU standards respectively set an ash content of 5% and 3% for wood pellets. Based on these standards, the post-harvest residues of tomato, pepper, and eggplant could have potentially initiate incineration and cause ash related problems in a burner.

The proximate analysis results were also confirmed by the elemental analysis data. Elemental composition differs depending on investigated plant parts. In general, biomass samples indicate a carbon content of 45–50%. The elemental analysis results show that the carbon contents in the analyzed samples were 38.25% for pepper stalks, and 40.29% for eggplant stalks. The H contents were measured as 5.34% for tomato stalks and 6.83% for eggplant stalks. The increase in C and H improves the fuel properties of biomass feedstock. Based on their C and H contents, the eggplant stalks indicated better biomass characteristics compared to the pepper and tomato stalks. The analyses results are also in alignment with the study by [15], who observed similar elemental composition for eggplant residues. Biomass N content also varies depending on plant parts; higher content in leaves (2.56%–4.00%) than in stems (0.15%–0.28%) [16]. High content of N and S generally are not desired nor required in biomass fuel due to the possibility of formation of gaseous emissions and possible ash related problems in a burner during combustion. However, the data presented in Table 1 may be average, yet satisfactory levels of quality of N and S within their roles in biomass and solid biofuel burning.

Overall, the evaluation of the proximate and ultimate analyses proved a satisfactory level of all investigated parameters, demonstrating the potential of tomato, pepper and eggplant post-harvest residues for producing biomass pellet fuel by direct combustion processes.

Pellet Characterization

After the proximate and elemental evaluations of the dry biomass samples, a commercial size pelletizing technology has been used for pellet production. The pellet characterization of the produced pellet samples from the post-harvest residues of tomato, pepper, and eggplant is presented in Table 2, comparing the results parameters to those of the sawdust and ISO and EU wood pellet standards. All three feedstock samples were successfully pelletized, and durable pellets were obtained, which indicated the feedstock's suitability for the densification process.

Bulk and individual pellet density are essential for densified pellets for handling, storage, and transportation, and a higher level is more desired. The obtained bulk density values were around the recommended values by the relevant ISO and EU standards, which suggest a density of >600 kg/m^3. However, the measurement values were observed to be all below the mandatory standard, though the obtained results were within the reported values for straw pellets [2]. Previously published research proved the bulk density of pellets from greenhouse melon harvest waste to be higher than 667 kg/m^3 [12]. Found the maximum bulk density of 350 kg/m^3 for tomato waste pellets [17]. The pellet bulk density parameter is related to the particle size distribution, applied pressure, characteristics of raw feedstock, moisture content, diameter, and pellets size. The smaller bulk density could be attributable to the applied pellet diameter of the present study. However, the ISO and EU standards indicate the mandatory values of 6 to 8 mm in diameter. On the other hand, the pellet unit density results proved the reported density for pepper residue [6], eggplant stalks [15], and tomato residue [5]. Notably, the samples showed a satisfactory bulk and pellet unit density (Table 2).

The moisture content of pellet samples varies between 10.2 and 11.5 for pepper and tomato, respectively. These values are close to the ones obtained for the raw materials, indicating the equilibrium moisture contents of specific materials. Low moisture content is very important to ensure good combustion [12], handling, storage, and transportation [3].

The three types of harvest residue pellets showed similar calorific values (i.e., HHV) to sawdust and lower boundary values compared to the ISO and EU standards. The proximate and ultimate analyses results contribute to the understanding of the calorific values of biomass pellet. The positive and negative contributor parameters might balance the calorific value of the tested materials. In fact, the HHV increases with an increasing C and H ratio. On the other hand, oxygen, moisture, and ash contents negatively correlate with HHV. The C content of the fuel is the primary resource of the heat generated during combustion. This result clearly indicates that the HHV of pelleted biomass can be potentially used for greenhouse heating.

An application that could help improve the referred parameters such as moisture content, ash content, and bulk density in accordance with the referred ISO and EU standards could be to dry sawdust and add more of it into the residues of other crops, e.g. pellets made out of pepper and sawdust.

Energy Potential

Most greenhouses are built at locations where climate conditions are more suited to year-round vegetable production based on either one or two crops production annually [11]. [18] reported an estimation of 1.3 kg/m^2 post-harvest residue for tomatoes in Italy. Similarly, [19] estimated 0.9 kg/m^2 of post-harvest residue for tomatoes on a dry weight basis. On the other hand, [11] estimated an average of 1.6 kg/individual plant harvest residue for tomatoes in fresh weight. Combining the above values and the average number of plants per square meter, which is in the range of 1.5 and 3.0, vegetable crop residues in a greenhouse are estimated to exceed 1.0 kg/m^2 on a dry weight basis, annually. This amount of waste can sustainably produce 17.50 MJ/m^2 of heating energy. Based on the information given in the introduction section, the average heat consumption in the greenhouse of the Mediterranean region is estimated at 200 kWh/ha.hr [8].

Greenhouse energy demand is determined by different factors such as local climate, temperature, and solar radiation. According to the long-term meteorological data on Sakarya, Türkiye, the annual temperature ranges from 2 to 30 °C, and the solar radiation has been estimated to be 1340 kWh/m^2. Based on the solar radiation intake of different world regions, the heating energy necessary to maintain an adequate temperature in a greenhouse Sakarya, the case city, has been assumed to be 300 kWhth (in the range of values specific to the conditions in the Mediterranean region and the conditions in the Netherlands) and corresponding to an annual demand of 3,066 MWhth per hectare (8,760 hours).

Assuming the average heating value of 4.86 kWh per kilogram of waste, 10 tons of waste residue per hectare can annually produce approximately 48,600 kWh of heating energy. Accordingly, this obtained heating energy can supply about 1.85% of the energy needed in an average greenhouse under the climatic conditions in Sakarya.

Moreover, the average greenhouse CO_2 demand is estimated to be almost 2,650 t/ha [15]. The carbon content of the tomato plant, including stem and leaves, has been reported to be as 18% [14]. Hence, the annual tomato waste would give approximately 1,800 kg C and 6,600 kg CO_2 per hectare. The excess CO_2, which is to enough to supply only about 0.4% of the annual CO_2 demand of an average greenhouse, could be fed into the greenhouse to support photosynthesis during low temperature and low photosynthetically active radiation (PAR).

CONCLUSION

This study focused on characterizing the greenhouse vegetable post-harvest residues of tomato, pepper, and eggplant for pellet production. Proximate and ultimate analyses of the investigated plant species were satisfactory for pellet fuel production. HHV values were 17.25 MJ/kg, 17.45 MJ/kg, and 17.80 MJ/kg for tomatoes, pepper, and eggplant harvest waste pellets, respectively, and comparable to the calorific value of sawdust pellet (18.30 MJ/kg). The moisture (10.20–11.50%) and ash (12.82–17.64%) contents were evaluated in investigating the harvest residues' suitability for energy generation by direct combustion. Thus, the investigated pellet input material proved its suitability as a promising feedstock for pellet biofuel production. According to the average heating value and dry plant harvest residue, it is possible to obtain 10 tons of wastes per hectare capable of producing 48,600 kWh of heating energy and 6,607 kg of CO_2 to be supplied to the greenhouse for photosynthesis. For an effective waste management strategy to ensure environmentally friendly treatment and utilization of such significant amounts of energy for greenhouse heating, the assumed pelleting technology proved its advantage and efficiency within the clean energy generation and CO_2 utilization. Future research on this line will focus more on both comparative and prospective life cycle assessment of different palletization technologies.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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