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Assessment of Biogas and Syngas Potentials of Cotton Stalks in Turkey

Nazife Işık HAYKIR*[1] ORCID *0000-0002-6657-9663*

[1]*Ankara University, Faculty of Engineering, Department of Energy Engineering, Ankara*

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Abstract

Turkey, being one of the largest producers of world cotton production, utilizes biomass through direct incineration for electricity generation which accounts for 1.5% of the total electricity generation in Turkey. In this work, biogas potential of cotton stalks was assessed to present a foresight to the future biomass valorizations in the country. Cotton stalks harvested in six cities located in the Southeastern, Aegean and Çukurova regions of Turkey were evaluated and discussed with respect to their potential in electricity generation and the invoiced electricity consumption in 2019. These cities were found to yield 15.6 million tonnes of cotton stalks with an annual 3.1 billion m^3 of methane and also, 12 TWh of electricity generation that could meet almost 32% of the electricity demand. For Southeastern region, region's electricity consumption could be met by 99.5% with the anaerobic digestion of cotton stalks (9 million tonnes/yr). Methane potentials of cotton stalks were compared with the corresponding syngas yields and lower percentages were obtained for syngas. Anaerobic digestion and thermochemical conversion of agricultural residues, being proposed as energy strategies in this study, could help to accelerate the activities on bioenergy share in Turkey.

Keywords: Cotton stalks, Anaerobic digestion, Biogas, Methane, Syngas

Türkiye'de Pamuk Saplarının Biyogaz ve Sentez Gazı Potansiyelinin Değerlendirilmesi

Öz

Dünya pamuk üretiminin en büyük üreticilerinden biri olan Türkiye, biyokütleyi doğrudan yakma yoluyla kullanmaktadır ve biyokütlenin elektrik üretimine katkısı %1,5'tir. Bu çalışmada, ülkenin gelecekteki biyokütle temelli uygulamalarına bir öngörü sunmak için pamuk saplarının biyogaz potansiyeli değerlendirilmiştir. Türkiye'nin Güneydoğu, Ege ve Çukurova bölgelerinde yer alan altı ilde hasat edilen pamuk sapları, biyokütlenin elektrik üretim potansiyeli ve 2019 yılı faturalı elektrik tüketimi açısından değerlendirilerek tartışılmıştır. Bu illere ait toplam pamuk sapı üretim kapasitesi 15.6 milyon ton olmakla birlikte, söz konusu biyokütlenin yıllık 3,1 milyar m^3 metan gazı ve ayrıca elektrik talebinin yaklaşık

*Corresponding author (Sorumlu yazar): Nazife Işık HAYKIR, *haykir@ankara.edu.tr*

%32'sini karşılayabilecek 12 TWh elektrik üretimine karşılık geldiği bulunmuştur. Güneydoğu Anadolu bölgesi için pamuk saplarının anaerobik çürütülmesiyle (9 milyon ton/yıl) bölgenin elektrik tüketiminin %99,5'inin karşılanabileceği tespit edilmiştir. Pamuk saplarının metan potansiyelleri, karşılık gelen sentez gazı verimleri ile karşılaştırılmış ve sentez gazı için daha düşük yüzdeler elde edilmiştir. Bu çalışmada enerji stratejisi olarak önerilen tarımsal kalıntıların anaerobik çürütülmesi ve termokimyasal dönüşümü, Türkiye'de biyoenerji üretimine yönelik faaliyetlerin hızlandırılmasına yardımcı olacaktır.

Anahtar Kelimeler: Pamuk sapları, Anaerobik çürütme, Biyogaz, Metan, Sentez gazı

1. INTRODUCTION

1.1. Electricity Production and its Dependency on Biomass

Worldwide interest in biogas production has been receiving attention as a low cost and clean technology promoting biocircular economy. Biogas not only combats with climate change and alleviate fossil fuel dependency, but it also promotes growth in rural areas, generation of organic fertilizer and management of wastes [1]. Biogas is ecofriendly and recognized to introduce healthy cooking replacements for developing regions. It has been reported that roughly 4 million people lost their lives due to unproductive use of solid fuels for cooking purposes [2]. Recently, International Energy Agency (IEA) has reported that global emissions have risen by roughly 2% from December 2019 to December 2020. CO_2 concentration in the atmosphere was reported 410 ppm in year 2018 as 33 billion tons of CO_2 emission took place in the same year [3]. This steady increase will continue as the destructive human activities will remain over the next centuries. For this reason, proposing sustainable strategies such as biogas generation for certain energy needs is noteworthy.

According to International Energy Agency (IEA), world gross electricity generation was 3.9% higher in 2018 than it was in 2017 [4]. In 2018, total production was mainly met by combustible fuels with 66.3%. As shown in Table 1, electricity production by coal and natural gas respectively constituted 38% and 23% of the total as the leading sources in 2018. On the other hand, the share by biofuels and waste corresponded to only 2.4% (IEA, 2020). For Europe, the largest percentage shared by the nuclear, natural gas and coal (Table 2). Biofuels including primary solid fuels, biogas and liquid biofuels totally made up about 4.1% of the electricity generation [5]. Biogas corresponded to 1.6% of the total generation in Europe [5] where installation of 18202 biogas plants were made according to European Biomass Association [6]. Based on the mentioned data, more effort is required to increase the role of biofuels and make biogas generation more prevalent.

In Turkey, electricity production is heavily dependent on coal, natural gas and hydropower as indicated in Table 3. Biomass as a fuel used in direct combustion provided about 1% of the electricity production in 2018 according to EPDK data [7]. Turkey represents a remarkable capacity for agricultural and livestock residues [8]. Valorization of these residues through anaerobic digestion for the production of biogas for its utilization in combined heat and power (CHP) plants rather than aiming direct combustion can lead to significant reductions in greenhouse gas (GHG) emissions [9]. Based on Turkey's Renewable Energy Action Plan (REAP), the use of renewable energy for electricity generation will be motivated by adding 34 GW of hydropower, 20GW of wind energy, 5 GW of solar energy, 1GW of geothermal and 1 GW of biomass energy by 2023. Thus, 30% of the electricity consumption will be met by renewable sources by 2023 [10]. According to Bioenergy and Food Security (BEFS) Assessment for Turkey, reaching 1 GW increase in biomass energy can be realized through the combination of biogas production by 768 MW and direct combustion by 244 MW from selected biomass within CHP concept [11].

Table 1. World gross electricity production by source in year, 2018 [4]

Source	Share (%)
Coal	38
Oil	2.9
Natural gas	23
Hydropower	16.2
Geothermal and tidal	0.5
Wind	4.8
Solar	2.1
Biofuels and waste	2.4

Table 2. Electricity generation by source in year, 2018 in Europe [5]

Source	Share (%)
Nuclear	22.4
Coal	21.3
Natural gas	19.6
Hydropower	16.1
Wind	9.7
Biofuels	4.1
Solar PV	3.2
Oil	1.4
Waste	1.3
Geothermal	0.48
Tide	0.01
Solar Thermal	0.12
Other sources	0.14

Table 3. Electricity production in Turkey in year 2018 [7]

Source	Electricity production in 2018 (GWh)	Share (%)
Hydropower	59.902,04	20.24
Coal (imported)	62.988,54	21.28
Natural gas	91.639,14	30.96
Lignite	45.087,00	15.23
Wind	19.827,00	6.70
Geothermal	7.430,98	2.51
Biomass	3.240,96	1.09
Bituminous coal	2.844,58	0.96
Asphaltite	2.328,50	0.79
Fuel oil	328,89	0.11
Solar	385,86	0.13
Diesel oil	0,22	0.00
Total	**296.003,71**	**100.00**

1.2. Cotton and Cotton Stalks Production

White gold of the agriculture, cotton is a popular industrial crop grown widely across the world and used for the fabrication of natural comfortable clothes that keeps the consumers skin dry in the summer and warm in the winter. It is important for ensuring employment particularly, for textile and agricultural industries [12]. Its production typically requires subtropical and seasonally dry tropical areas in both the northern and southern hemispheres [13]. Cotton plant is fundamentally made up of bolls and straws. The seeds of the plant are found in the bolls where fibers grow. The straw section which left on the field right after the harvest are also referred to as cotton stalks. Cotton stalks are principally the straw, emptied balls, and leaves. Normally, these residues, are buried or burned for the following seeding. However, this brings the release of harmful gases and deteriorates soil fertility [12].

According to International Cotton Advisory Committee (ICAC), total cotton production was reported to be 26.4 million tonnes and the average yield was 775 kg/ha for 2019-2020 season. Since the Asian economies have a significant leading potential regarding cotton consumption, consumption was around 26.2 million tonnes [14]. Turkey is one of the major cotton producers in the world and has the 6th place following India, United States and China. Based on the ICAC's report for March 2020, Turkey also has a significant place considering the area planted and the yield (Table 4). Turkey shares 3.1% the total production. Besides, it is ranked 4th with respect to cotton consumption which is 6.3% of the total world consumption with 1.63 million tonnes. USA falls behind China and India in the total production [15].

As shown in Table 4, the top producer India appears at the bottom of the list with respect to cotton fiber yield and produce cotton yields lower

Table 4. World cotton production for 2019/2020 season [15]

	Countries	Fiber cotton production (000 metric tonnes)	Cotton plantation area (000 ha)	Fiber cotton yields (kg/ha)
1	India	6000	12700	472
2	China	5800	3300	1758
3	USA	4310	4177	1032
4	Brazil	2850	1622	1718
5	Pakistan	1320	2631	513
6	***Turkey***	***815***	***520***	***1567***
7	Uzbekistan	640	900	712
8	Mexico	369	224	1644
9	Argentina	358	485	737
10	Turkmenistan	307	545	564

than the average. On the other hand, Turkey is one of the best countries with the highest amount of cotton production per unit area. Regarding the position of Turkey with respect to the production and the yield and employment in the cotton industry which is around 2 million people [16], considering by-products of this industrial crop for bioenergy production is as important strategy.

According to TUIK 2018 data, the regions that possess the largest cotton production are Southeastern region including Şanlıurfa and Diyarbakır, Aegean region including Aydın and İzmir, and Çukurova region including Adana and Hatay (Table 5). These cities hold the largest production being 85% of the total in 2018. Cotton stalks are among the most abundant crop residues (spreaded in the field) in Turkey. Total production capacity of cotton stalks is around 18.5 million tonnes annually [11, 14]. Şanlıurfa is in charge of almost 50% of the total cotton stalks production (Table 6).

Table 5. Cotton and cotton stalks production by regions in 2018 [11,14]

Order	Regions	Cotton (raw) production (tonnes)	Cotton stalk (tonnes)*
1	Southeastern region including Şanlıurfa and Diyarbakir	1272150	9134037
2	Aegean region including Aydın and İzmir	436900	3136942
3	Çukurova region including Hatay and Adana	462600	3321468
	Others	398350	2860153
	Total	2570000	18452600

*Calculated according to Equation 1

Table 6. Top cotton stalk producer cities in Turkey [11,14]

Order	Cities	Production capacity (tonnes)
1	Şanlıurfa	7381040
2	Aydın	2029786
3	Hatay	1845260
4	Diyarbakir	1752997
5	Adana	1476208
6	İzmir	1107156

1.3. Anaerobic Digestion of Biomass and Effect of Biomass Pretreatment

Biogas production takes place by the anaerobic degradation of organic matter mainly into a gaseous mixture and residual solids [17]. During this anaerobic process, four successive steps, hydrolysis, acidogenesis, acetogenesis and methanogenesis are performed by the interaction of distinct microorganisms [18]. The gaseous product includes primarily methane (50-70%) referred to as biomethane and carbon dioxide (10-50%), and some minor gases such as hydrogen sulfide and ammonium in the range of parts per million to a few percent [19].

A wide plethora of raw materials has been offered as energy sources for the production of methane, ranging from municipal waste to food waste and from lignocellulosic biomass to animal manure [20]. Although each possesses the advantage of being abundant and low cost, certain structural restrictions impede the efficient digestion of biomass. For lignocellulosic biomass such as agricultural and forest residues, energy crops, paper wastes and municipal waste [21] which is principally made up of cellulose, hemicellulose and lignin, recalcitrance is the barrier for the release of fermentable sugars [21]. Recalcitrance is the combination of factors such as heterogeneity, cellulose crystallinity and the presence of lignin [22,24]. These factors lead to low biogas yields and slow degradation rates from lignocellulosic feedstocks. For this reason, pretreatment should be conducted to make simple sugars, amino acids and fatty acids easily accessible for the microbial community. Physical strategies such as comminution in combination with chemical pretreatments such as dilute acid pretreatment or alkaline pretreatment could work well for many lignocellulosic feedstocks [25]. Previously, rice straw pretreated via acids, hydrochloric acid, oxalic acid, acetic acid and citric acid at dilute concentrations was used for biogas production. While oxalic acid gave the best performance concerning enzymatic yields, the highest biogas production was achieved through anaerobic digestion of oxalic and citric acid pretreated biomass [26]. In another study, alkaline pretreatment of birch with 7 wt.% NaOH at 100°C resulted in 50% higher methane production compared to methane production from untreated birch [27]. Ionic liquid (IL) pretreatment has been also explored concerning its effect on biogas production from lignocelluloses. 1-butyl-3-methylimidazolium chloride (BMIMCl), which partially delignified rice straw and disrupted biomass crystallinity upon pretreatment at 140°C for 2 h, improved methane yields from biomass; 233 ml CH_4/g biomass was obtained [28]. Another work successfully demonstrated the impact of mechanical, chemical, and enzymatic pretreatments on biogas production from switchgrass. Performing different combinations of pretreatments, such as grinding-alkaline pretreatment-autoclaving and mulching-enzymatic-alkaline pretreatment resulted in diverse methane yields [29] since there have been principally reductions in the lignin and hemicellulose content of the biomass, disruptions in the crystallinity of cellulose, and an increase in the available surface area.

In this work, methane and electricity generation potentials of cotton stalks were explored for certain regions of Turkey; Southeastern, Aegean, and Çukurova regions. Cotton stalks were initially investigated concerning their composition and evaluated through their proximate and ultimate analysis. Calculations were performed on the basis of the experimental results and the eventual findings were interpreted by considering the electrical potentials of the biomass that meet the latest consumptions of the regions and the cities. Accordingly, this study aims to present a biorefinery perspective to one of the most recognized agricultural wastes of Turkey; cotton stalks.

Table 7. Studies on biogas production from cotton stalks

Cotton stalks particle size	**Pretreatment method**	**CH_4 yield (mL/g volatile solids)**	**Benefits of pretreatment**	
< 0.45 mm	Not applicable	70.2	-	[42]
<2 mm	Thermophilic microbial consortium that hydrolyze cellulase and hemicellulose for 10 days	111	122.4% higher methane yield relative to untreated biomass	[43]
<3 mm	Hydrothermal pretreatments using hot water liquid, dilute ammonia, recycled liquid from anaerobic digestion	241.6	4.58-fold increase relative to untreated biomass	[44]
<1.19 mm	Acid pretreatment with H_2SO_4 at 0.9% (w/w), 100°C for 60 min Alkaline pretreatment with NaOH at 4% ($W_{NaOH}/W_{biomass}$)	449 (co-digested with swine manure at a mixing ratio of 50:50)	31.7% higher methane yield relative to untreated biomass	[45]
1-3 mm	Steam pretreatment with supercritical CO_2 at 100 bar, 180°C for 140 min Organosolv-supercritical CO_2 at 100 bar, 180°C for 140 min	177	Reduction in optimal digestion time from 30 days to 20 days with pretreatment 29% higher methane yield relative to untreated biomass	[46]
<1 mm	Pretreatments for 24 h with KOH at 1.5-6% (w/w), NaOH at 1.5-6% (w/w), $Ca(OH)_2$ at 1-4% (w/w) (w/w),Alkali hydrogen peroxide at 1-4% (w/w), H_2SO_4 at 1-4% (w/w), H_3PO_4 at 1-4% (w/w),Steam explosion at 0.9-1.5 MPa for 5-15 min	192	254.3% higher methane yield relative to untreated biomass	[47]
<1 mm	Pretreatment with 4% (w/w) ammonia solution at 80°C for 12 h	218.9	2.71-fold increase relative to untreated biomass	[48]

2. MATERIALS AND METHODS

Cotton stalks derived from the cotton plant (*Gossypium hirsitum*) were obtained from Aegean region of Turkey, air dried and ground with a hammer mill (APEX 314-HP 5.5). They were then sieved to a particle size less than 1 mm. Sulfuric acid, calcium carbonate, ethanol and the standards; D-glucose and D-xylose were purchased from Merck.

Elemental analysis of the cotton stalks was conducted with LECO, CHNS-932 Elementary Chemical Analyzer. Hitachi Simultaneous

Thermogravimetric Analyzer (TGA) STA 7300 was used to perform the proximate analysis of the biomass (Figure 1). Ash, extractive compositional content of the biomass were measured using the analytical procedures published by the National Renewable Energy Laboratory in Colorado, USA. (NREL) [49-51]. The related data are given in Table 8.

Annual cotton stalks production was calculated according to the following formula,

$$\text{Cotton stalks}\left(\frac{\text{tonnes}}{\text{year}}\right)=\text{Cotton production}\left(\frac{\text{tonnes}}{\text{year}}\right)\times\text{RCR} \quad (1)$$

RCR, residue to crop ratio, is defined as the amount of residues generated to the amount of crop produced and it is dimensionless. This residue yield is a measure of the value of the crop used. For cotton stalk, RCR was obtained as 7.18 according to the literature data collected and verified by General Directorate of Agricultural Research of Turkey (TAGEM). This value is quite high when compared to those determined for cereals (0.10-1.41), fruits (0.2-0.55) and oil seeds (0.1-1.29) indicating the potential of cotton stalks for bioenergy and biomaterials applications [11].

Methane yields were calculated using the Buswell equation (Equation 2) and Equation 3,

$$C_nH_aO_bN_c+\left(n-\frac{a}{4}-\frac{b}{2}-\frac{3c}{4}\right)H_2O\rightarrow \left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-\frac{3c}{4}\right)CH_4+ \left(\frac{n}{2}-\frac{a}{8}+\frac{b}{4}+\frac{3c}{4}\right)CO_2+cNH_3 \quad (2)$$

$$\text{MMY}\left(\text{mL(g VS)}^{-1}\right)=\frac{22.4\times1000\times\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-\frac{3c}{8}\right)}{12n+a+16b+14c}\times \left(1-\%lignin-\%ash\right) \quad (3)$$

where MMY is the maximum methane yield per unit mass volatile solids in the biomass, %lignin and %ash are the percentage lignin and ash contents in the biomass. n, a, b, c are coefficients in the empirical formula of cotton stalks determined from the elemental analysis [47,52].

Gross calorific value of the biomass was determined accordingly,

$$\text{HHV}_{biomass}\left(\text{MJ } kg^{-1}\right)=\{33.5[C]+142.3[H]-15.4[O]-14.5[N]\}\times10^{-2} \quad (4)$$

where HHV is the higher heating value of cotton stalks per unit mass of biomass. The elements in the brackets

Table 8. Proximate, ultimate and compositional analysis of cotton stalks

Ultimate analysis (wt. %)	
Carbon	44.4
Hydrogen	5.70
Nitrogen	1.40
Sulfur	0
Oxygen[a]	48.5
Proximate analysis (wt. %)	
Total solids	92.9
Volatile solids (VS)	75.0
Fixed carbon (FC)	11.1
Ash	6.9
Empirical elemental formula	$CH_{1.5}O_{0.8}N_{0.03}$
Compositional analysis (%)	
Extractives	10.4
Cellulose	36.4
Hemicellulose	13.7
Lignin	25.5
Calorific value (MJ kg^{-1})	
Higher heating value (HHV)	15.3
Lower heating value (LHV)	14.1

3. RESULTS AND DISCUSSION

3.1. Cotton Stalks Characterization

Table 8 shows the elemental, proximate and compositional analysis of cotton stalks. Accordingly, cotton stalks were found to possess a gross calorific value of 15.3 MJ kg^{-1}. The elemental formula of the biomass was determined as $CH_{1.5}O_{0.8}N_{0.03}$. Both the HHV and the elemental formula of cotton stalks were in accordance with the previously reported literature work [36, 54, 47]. Cellulose, hemicellulose and lignin were found respectively as 36.4%, 13.7% and 25.5%. Percentages of volatile solids (75%) and fixed carbon (11.1%) were determined according to the TGA analysis of biomass (Figure 1). Using Equation 2, maximum methane yield (MMY) of cotton stalks was determined as 271 mL/g VS which corresponded to 203 mL/g biomass.

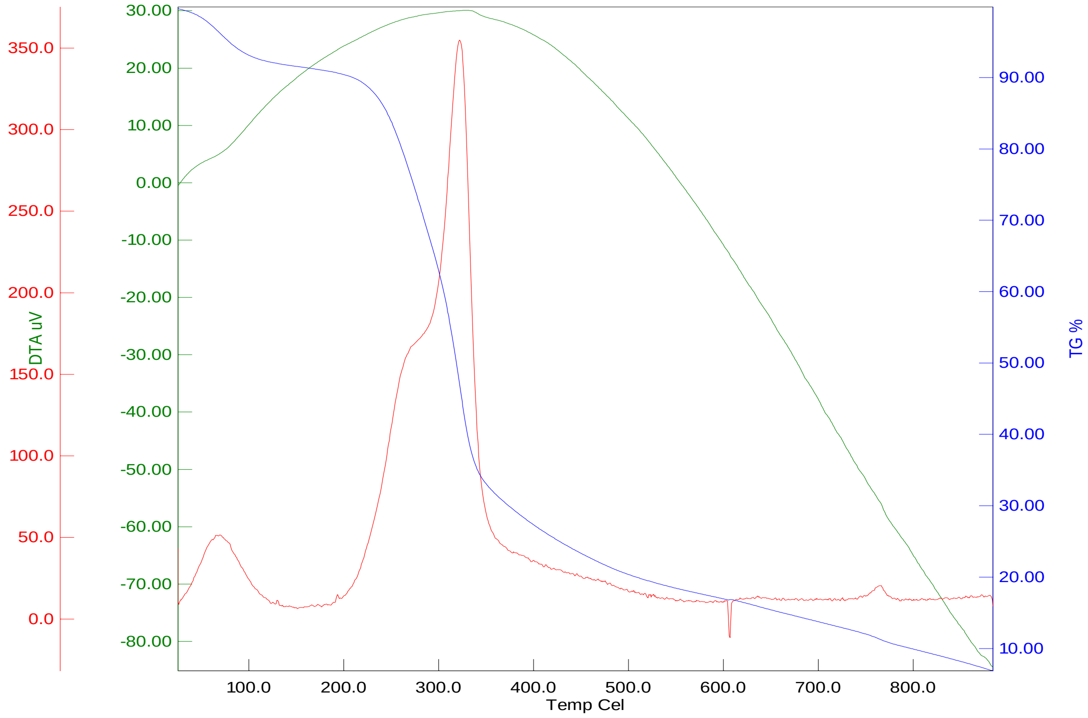

Figure 1. TGA analysis of cotton stalks

3.2. Anaerobic Digestion of Cotton Stalks

The maximum methane and electrical energy potential of six cities' possessing the largest capacity of cotton production were evaluated and presented in Table 9. Table 9 shows the cotton stalks production capacity, volumetric methane production from cotton stalks, electricity generation from methane and invoiced electricity consumption for year 2018. Electric efficiency was assumed as 40% [55] and used in the calculation of electricity generation in MWh for each city. According to the table, Şanlıurfa region contributes to cotton stalks production with 7.4 million tonnes/yr and methane production with 1.5 billion m^3/yr. The corresponding electricity generation was found 5.8 TWh/yr which was around 1.2-fold higher than Şanlıurfa's invoiced electricity consumption in 2019. Aydın located in the Aegean region comes after with roughly 2 million tonnes capacity. Aydın was found to generate 1.6 TWh of electricity from cotton stalks derived methane being 60% of the electricity utilization. Electricity generation from the Diyarbakir's cotton stalks production potential was found 54% of the invoiced electricity consumption. Regarding İzmir, which is the third-most populous city in Turkey and the largest in the Aegean region, the electricity generation by cotton stalks could only provide 5.7% savings. For İzmir potential sources, municipal waste and livestock manure can provide better electricity savings by biogas production. A previous study proposed a model for the management of these wastes by the implementation of a municipality-owned centralized system constituting eight biogas plants and evaluated the feasibility of the model. Accordingly, the unit cost of electricity was determined as 10 $ cent/kWh [56]. For İzmir, biogas production from cotton stalks could save only 27% for electricity consumption in commerce [7]. Regarding Çukurova region, roughly 33.4% and 32.3% savings were obtained for Adana and Hatay, respectively.

In total, cotton stalks were found to yield 3x10^9 m^3 of methane annually and a corresponding electricity generation of around 12 TWh/yr. For Southeastern Anatolia region, electricity generated from cotton stalks derived methane was calculated roughly as 7.2 TWh/yr. This potential can fulfill up to 35% of the electricity consumption in the entire region counting the energy demands of the cities, Gaziantep, Batman, Adıyaman, Siirt, Mardin, Kilis and Şırnak as well. Methane production from İzmir and Aydın's cotton stalks capacity was found to meet almost 13% of the entire region electricity consumption. Çukurova region including, Osmaniye and Mersin, reached around 21 TWh invoiced electricity consumption in 2019. Cotton stalks derived from Adana and Hatay were found capable serving roughly 12% of the total if being valorized for methane generation.

Table 9. Biogas potential of the major cotton producer cities in Turkey

Region/city	**Cotton stalk production potential (tonnes/yr)**	**Methane production potential (m^3/yr)**	**Electricity generation potential (MWh/yr)**	**Invoiced electricity consumption (MWh/yr)**	**Demand met (%)**
Southeastern region	9134037	1854209511	7253668	7292615	99.5
Şanlıurfa	7381040	1498351120	5861550	4696184	124.8
Diyarbakır	1752997	355858391	1392118	2596431	53.6
Aegean region	3136942	636799226	2491159	18209780	13.7
İzmir	1107156	224752668	879232	15511094	5.7
Aydın	2029786	412046558	1611926	2698686	59.7
Çukurova region	3321468	674258004	2637697	12812409	20.6
Adana	1476208	299670224	1172310	6754795	17.4
Hatay	1845260	374587780	1465387	4390056	33.4
Total	15592447	3165266741	12382523	38314804	32.3

3.3. Gasification of Cotton Stalks

Combustion of cotton stalks after harvesting is another option to use it as a source of energy. Energy density of cotton stalks being between 14.5-18.1 MJ/kg was found comparable to that of wood (17.4–18.6 MJ/kg). Direct incineration of cotton stalks has been reviewed in several works, pros and cons were put forward. Good burning efficiency was mentioned for cotton stalks and longer burning time was related to the density of the biomass [57]. Although the ash content of biomass is much lower compared to coal, cotton stalks were found to possess 6-8% ash on dry basis which is a higher amount compared to some common agricultural residues, wheat straw and corn stover and also, wood dust [58]. Apparently, ash not only act as a component to lower the calorific value of the biomass but also creates issues of slagging and fouling causing heat transfer limitations in the boilers [59]. Regarding the emissions contributing to atmospheric pollution, biomass combustion stands against climate change strategies. At this point, biomass gasification emerges as an important thermochemical route possessing several advantages over direct combustion. Production of syngas as an important versatile mid-product and the production of lower amounts of air pollutants are among significant benefits of biomass gasification. In gasification, biomass is subjected to temperatures around 600-900 °C or even elevated values in the presence of a gasifying agent (air, oxygen, steam, CO_2, or mixtures of these components) in which conversion to a mixture of gaseous products comprising mainly, carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2), a solid product, char and a viscous liquid product, tar is performed [19]. The principal aim of this thermochemical process is to produce synthesis gas, in short, syngas, CO and H_2 which can be valorized into a wide plethora of products, chemicals, liquid fuels and H_2 to generate heat and power [60]. Heating value of syngas was reported to change between 10-15 MJ/m^3 and 3-6 MJ/m^3 in case of steam and air employed as the gasifying agents, respectively [61]. An earlier literature work reported the gasification of cotton stalks into syngas using a bubbling fluidized bed gasifier [62]. The calculations for this section was performed according to the product gas composition measured in the mentioned study (Table 10). Gasification temperature was 770°C and steam was used as the gasifying agent at 0.52 steam: fuel ratio ((kg/h)/(kg/h)). Based on the given composition and atomic species balances, biomass to syngas conversion yield was calculated as 1.73 m^3 syngas/kg cotton stalks which was in accordance with the previously reported yields for a variety of lignocellulosic feedstocks such as rice husk, nut shell, pine and eucalyptus [63]. HHV of the syngas was calculated according to the given equation and found as 6.15 MJ/m^3.

$$HHV_{syngas} = 12.745 \times \%H_2 + 12.63 \times \%CO + 39.819 \times \%CH_4 \quad (5)$$

Table 10. Composition of the product gas obtained after gasification of cotton stalks [62]

Product gas	**Vol. %**
CO	15.16
CO_2	9.09
CH_4	4.29
H_2	23.18
O_2	0.86
N_2	47.44
HHV (MJ/m^3)	6.51
Cotton stalks to syngas conversion yield (m^3/kg)	1.73

Assuming electric efficiency of 15% for a steam turbine, the electrical energy production from the combustion of the syngas derived upon cotton stalks gasification are given in Table 11. Accordingly, annual electricity generation from syngas was found much less compared to that obtained from biogas. Although higher volumes of gaseous products were obtained from cotton stalks through gasification, electrical energy potential were lower due to the lower HHV_{syngas} being almost one sixth $HHV_{methane}$. For Southeastern region, syngas was found to meet almost 59% of electricity demand with roughly 16 billion m^3 of syngas potential. Besides, electricity generated from syngas in Aegean and Çukurova regions was approximately 8% and 12% of the electricity consumptions, respectively. For Aydın, cotton stalks derived syngas could meet almost 35% of the city's electricity demand.

Table 12 introduces a comparison between two processes from different perspectives. Although anaerobic digestion introduced a lower biomass to fuel conversion, 0.258 m^3/kg, estimated electricity generation was almost 2-fold higher compared to the electrical energy provided by the syngas. Gasification does not necessitate chemical or biological pretreatments since ground raw materials can directly be transformed into value-added gaseous products in hours via thermochemical reactions. Despite entailing a biomass deconstruction step particularly for lignocellulosic feedstocks prior to degradation of the organic matter, anaerobic digestion provides an efficient and clean source of energy for heating and cooking purposes at the household levels. For this reason, putting more research effort is important to motivate the installation of small and pilot scale digesters in certain regions of Turkey for the valorization of agricultural residues.

Table 11. Syngas potential of the major cotton producer cities in Turkey

Region/city	Cotton stalk production potential (tonnes/yr)	Syngas production potential (m^3/yr)	Electricity generation potential (MWh/yr)	Invoiced electricity consumption (MWh/yr)	Demand met (%)
Southeastern region	9134037	15801884010	4286261	7292615	58.8
Şanlıurfa	7381040	12769199200	3463645	4696184	73.8
Diyarbakır	1752997	3032684810	822616	2596431	31.7
Aegean region	3136942	5426909660	1472049	18209780	8.1
İzmir	1107156	1915379880	519547	15511094	3.3
Aydın	2029786	3511529780	952502	2698686	35.3
Çukurova region	3321468	5746139640	1558640	12812409	12.2
Adana	1476208	2553839840	692729	6754795	10.3
Hatay	1845260	3192299800	865911	4390056	19.7
Total	15592447	26974933310	7316951	38314804	19.1

Table 12. Comparison of anaerobic digestion and gasification of cotton stalks

	Anaerobic digestion of cotton stalks	**Gasification of cotton stalks**
Total electricity generation (TWh/yr)	12	7.3
Fuel/biomass yield (m^3/kg)	0.258 m^3 CH_4/kg biomass	1.73 m^3 syngas/kg biomass
HHV_{fuel} (MJ/m^3)	39.819	6.51
Advantages	Requires moderate operation temperatures. Promotes development for rural areas. Generation of high-quality rich fertilizer. Co-digestion of nitrogen rich resources with cotton stalks can increase methane yields.	Requires shorter residence times. Syngas represents a significant platform for the production of liquid fuels, hydrogen and chemicals. Reduced environmental concerns and better efficiencies compared to direct incineration.
Disadvantages	Requires elaborate pretreatment techniques and longer residence times.	Requires gas cleaning. Elevated operation temperatures and pressures.

4. CONCLUSIONS

This work demonstrated the electrical energy potential of cotton stalks from six cities that hold the largest cotton and cotton stalks production capacities in Turkey. For Southeastern region contributing to the biomass production with around 50%, significant savings were obtained. Electrical energy generation with 7.2 TWh/yr was found capable of meeting 35% of the region’s entire electricity consumption. For Aydın being the second greatest cotton producer in Turkey, 60%

saving was achieved. These findings were significant to show the potentials of native energy sources of the country and encourage the implementation of bioenergy facilities.

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