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From Agricultural Waste to Energy: Assessing the Bioenergy Potential of South-Central Texas

Ömer Ertuğrul [1,*], Bassel Daher [2,3], Gülden Özgünaltay Ertuğrul [1] and Rabi Mohtar [2,4]

[1] Department of Biosystems Engineering, Faculty of Agriculture, Kırşehir Ahi Evran University, 40100 Kırşehir, Türkiye; gozgunaltay@ahievran.edu.tr
[2] Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77845, USA; bdaher@tamu.edu (B.D.); mohtar@tamu.edu (R.M.)
[3] Texas A&M Energy Institute, College Station, TX 77843, USA
[4] Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77845, USA
* Correspondence: oertugrul@ahievran.edu.tr; Tel.: +90-(386)-280-4810

Abstract: This paper addresses the challenge of meeting increasing energy needs by assessing the potential of bioenergy as a sustainable resource option in South Central Texas. Available agricultural crop residues suitable for bioenergy production are evaluated from the 21 counties in South Central Texas Regional Water Planning Area (Region L). The residues produced and available for bioenergy are quantified according to the production areas for each field crop and tree area. Residue-to-product ratios of field crops are determined according to crop type and production quantity. Biomass potential of trees is calculated based on tree density and biomass production per tree. The results demonstrate that the potential productions of utilizable agricultural wastes are in the range of 898.7 t kt–1421.39 kt for Region L. The average annual energy potential is estimated at 19.27 PJ, and ranges between 14.36 and 24.18 PJ. The average potential biomass-based electricity production could compensate significant amount of coal-based electricity generated in the Texas and when agricultural wastes are available.

Keywords: alternative energy sources; biomass; crop residue; potential assessment; renewable energy; sustainability

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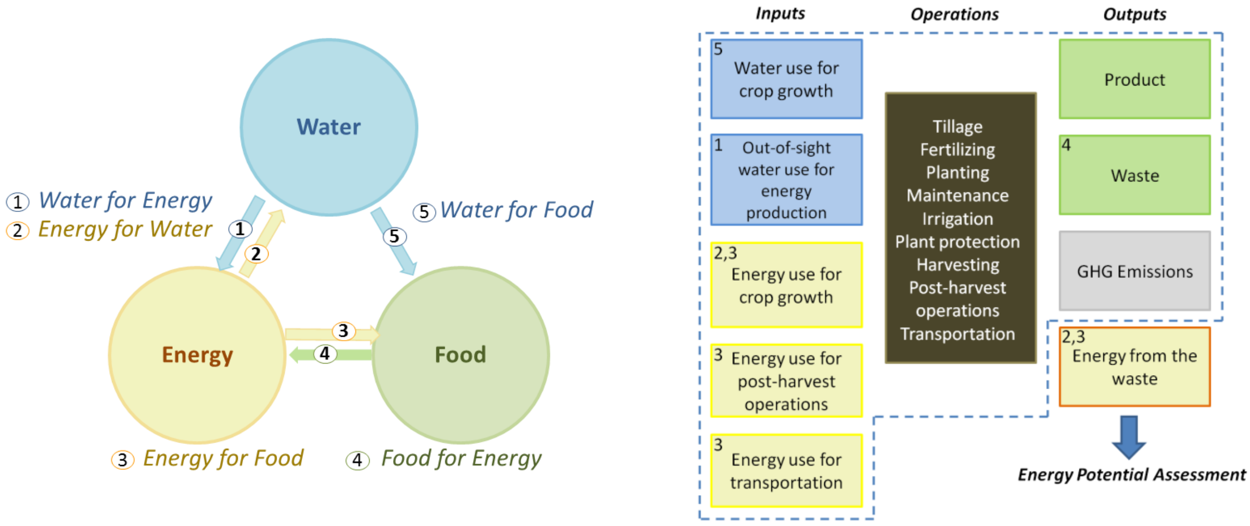
1. Introduction

The new report on Sustainable Development Goals of United Nations expresses ensuring access to affordable, reliable, and sustainable energy for all [1]. Utilizing potential energy sources will contribute to this goal. In this respect, agricultural production that mainly aims to provide food and other needs also is a potential energy source by providing crop wastes. Utilizable amounts of agricultural wastes can provide a good source to various final energy types as fuel for vehicles, electricity and heat for homes and industry [2,3]. To obtain the most efficient resource system, instead of growing crops to produce energy by consuming water, energy and covering land, providing necessary food and seizing upon the potential of crop waste would be more beneficial and prevents possible conflicts of bioenergy and water supplier sectors [4]. Upon this, providing more productive evaluation with specialized models require high resolution data in regional basis which supports creating the divergent policies held by different regional structure, and to build healthier communication and political strategies accordingly [5–10].

Biomass can be provided by agricultural production, such as crop residues from field crops and wood residues from horticultural production. Although the expression of residues varies in the literature, stalk, straw, husk, cob, boll, shell, and pod are the residues that can be used as by-products of agricultural production.

Biomass is mentioned in the renewable portfolio of 26 States of US, where biomass can be advantageous, as a qualifying renewable resource to reach their individual renewable target for electricity generation [11]. Non-hydroelectric renewable sources contributed 5,768 GWh to Texas's net electricity production, which is 37,370 GWh in total, and there is an expectation of a strong growth of renewable electricity generation until 2030 [11,12]. Therefore, biomass emerges as a serious option to be considered as a source of electricity generation.

As a dimension of the water, energy, and food nexus, the connection between energy and food can be represented by the evaluation of energy production potential from agricultural residues [13]. Therefore, agriculture is an important input for energy production (Figure 1).



(**a**) (**b**)

Figure 1. (**a**) Interrelations of inputs/outputs within the WEF nexus system framework are explained by numbers. (**b**) The bioenergy potential assessment of agricultural residues in the crop production system as a main focus of this paper, whereas dashed blue line demarcates the traditional business as usual loop.

It is possible to manufacture bio-fuel through biomass by using water and energy as inputs [14,15]. In this sense, this paper aims to perform the following:

- Identify the type and spatial distribution of crops that provide the highest share of potential residues and energy production in South Central Texas;
- Quantify the potential energy that could be produced by food crops and trees;
- Evaluate the contribution of potential biomass energy production of the region as part of the energy portfolio of the State;
- Provide a contribution to the holistic WEF Nexus compatible solutions on the side of food for energy.

2. Previous Research

Much research in recent years has focused on the possible contribution of biomass to the energy sector depending on its advantages, among which are a reduction in the reliance on fossil fuels, the possibility of enhancing rural economies by utilizing previously under-utilized waste, and the achievement of a carbon neutral life cycle. Guresci (2020) [16] conducted a literature review including general information from scientific articles and research reports about biomass energy and the biomass energy potential of Türkiye. There is research stating that forest and agricultural residues as biomass sources have great potential to improve rural energy services. Tun and Juchelková (2019) [17] determined the biomass energy potential of Myanmar by considering agricultural residues, wood residues, livestock, and poultry residues. To calculate the waste amounts of agricultural residues and wood residues, residue-to-product ratios (RPR) multiplied with production data have been used. Energy potentials were calculated by multiplying the residue values with lower heat values (LHV). They stated that biomass energy has a great importance to provide sustainable development Myanmar by increasing energy self-sufficiency. Matindi et al. (2018) [18] investigated the supply chain system of Australia and concluded that transporting and collection periods have a high impact on the optimization of a healthy bioenergy production system, which is an advantage for Texas in terms of locations of delivery end points. Studies on determining biomass potential and revealing usage possibilities based on the values obtained through compilation studies have also been published in reputable journals. In this sense, biomass potential and opportunities for use were investigated and substantial potentials of biomass energy for climate change mitigation and energy sustainability were determined [19,20]. In this study, residues, availability to residues, and energy equivalents in terms of electricity are determined and mapped by preferring the methods used in previous studies published in reputable journals; for example, a study by Karaca (2015) [21] focuses on mapping the biomass energy potential of field crops and horticultural products, using these to determine residues by taking into account residue-to-product ratios (RPR), availability (A), and lower heat values (LHV), similarly to the following publications: Tun and Juchelková (2019) [17] focused on agricultural and wood residues by using residue-to-product ratios (RPR) and lower heat values (LHV); Hiloidhari et al. (2014) [22] focused on surplus residues that can be defined as available residues of field and horticultural crops by using residue-to-product ratios (RPR) and heating values to calculate the bioenergy potential in India; Milhau and Fallot (2013) [23] investigated the bioenergy potential of India and focused on agricultural residues by using residue-to-product ratios (RPR), a recoverability factor after agricultural uses that can be defined as availability; Jiang et al. (2012) [24] investigated over a ten-year period the bioenergy potential of China by calculating residue potential by using residue-to-product values and converting them to the energy potential of coal equivalent; Al-Hamamre et al. (2014) [25], in addition to biogas potential, also investigated the bioenergy potential of agricultural products in Jordan by using RPR and average heat values. Among those studies, Karaca produced a spatial database in ArcGIS software and mapped the findings in low-resolution accordingly, while Jiang et al. produced a high-resolution mapping which is limited in this study as county-based since the locations of agricultural production data are unmatchable with parcels in the US.. However, there are also concerns about biomass resources. Since one of the main bioenergy processes for generating electricity is direct combustion of agricultural wastes [26,27], pollutant facts have been discussed in the literature [28,29]. It is hoped that optimized modern grate combustion plants consisting of air staging strategies will enable low emission operations [30], and recent developments of carbon capture and sequestration technologies are promising in the reduction in carbon emissions in power plants [31].

3. Materials and Methods

3.1. South Central Texas Regional Water Planning Area (Region L)

To offer solutions in terms of planning the Water–Energy–Food Resources Nexus in San Antonio and surrounding regions, the San Antonio Case Studies Project has been conducted by Texas A&M University WEF Nexus Initiative. The region referred to as South Central Texas Regional Water Planning Area, which is the focus of the project, includes 21 counties as depicted in Figure 2 [32].

To complete the missing knowledge at the WEF Nexus system of the region, the determination of the energy potential derived by agricultural biomass sources to explain food for energy part constitutes the motivation of this research.

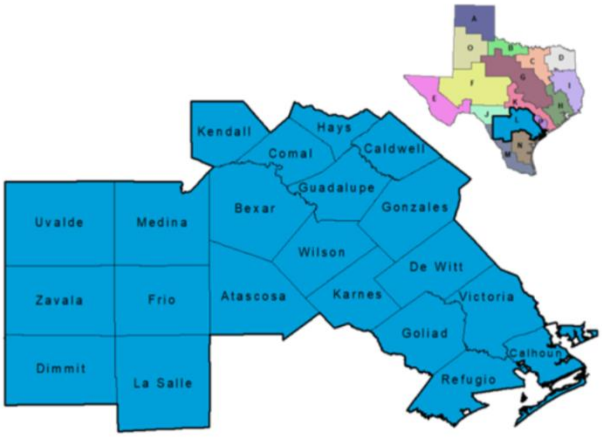


Figure 2. South Central Texas Regional Water Planning Area (Region L) and its boundaries along with counties within the region [32].

3.2. Data

The available data are for the years 2007, 2012, and 2017, providing annual production amounts of wheat, oats, corn, cotton, peanuts, rice, soybean, sorghum, and sunflower, and the production area of pecan and peaches, which are gathered for 21 counties in South Central Texas Regional Water Planning Area (Region L) from the USDA Census [33]. The USDA Census gathers the data every five years and publishes them with a delay of two years. The units of quantities are standardized to metric tons.

Pecan and peaches are the only tree products that have available data and research in the literature. Number of trees values are calculated according to data of tree density from the literature [34,35] and production area [33]. Wood energy is available in the form of wooden chips, fuel wood, wood waste, and wood pellets, and it is also produced to a very limited extent from willow crops in short-rotation forestry. The majority of wood harvested ends up as wood energy directly or indirectly after having been used for other daily support material purposes first [15]. It should be noted that the woody biomass amount associated with pecan and peach trees only include residues derived from orchard management activities like pruning, thinning, and shell leftovers.

3.3. Calculations of Available Biomass and Corresponding Energy Amount

Potentially available crop residues for energy production can be considered as the production leftover that is not used [23]. Most research focused on the determination of the residue-to-product ratios (Table 1), availability of agricultural wastes as potential energy sources, and calorific values of crops globally, nationally, and regionally (Table 2). The general trend in determination of potential amount of residues generated is calculated by considering crop yields on the main product and residue-to-product ratios [21,36].

Residue-to-product ratios (RPRs) are determined for the field crops based on the literature review presented in Table 1. The following crop residues are considered: crop residues are stalk and straw that remain on the field after the harvest, and corncob, rice husk, cotton husk and boll, peanut shells, soybean pods, and wheat pods that are obtainable with post-harvest operations. Since there is no information relating to variety mentioned in the statistical data of USDA Census, it is necessary to obtain a wide range of RPR values [36]. Therefore, estimations of the average, minimum, and maximum amounts of residues have been perform to consider yearly variability in residue amounts at county level (Table 1). The potential of available residues of field crops are determined using the average availability ratios of residues (Table 2). The potential of the available agricultural residues in the counties of South-Central Texas is calculated by Equation (1), which has been used in a considerable number of publications [16,20–24].

$$ACR = P \cdot RPR \cdot A \quad (1)$$

where the following are defined: *ACR*: Available crop residue (kg); *P*: Production (kg); *RPR*: Residue-to-product ratio; *A*: Availability (%).

Assuming the power plant technology as fixed-bed (grate) combustion, the technology basically works by burning biomass directly to produce steam that turns a turbine to drive a generator, thus producing electricity [18]. Energy potentials of the residues are calculated by Equation (2) [16,20–22,24], available residue amounts, and calorific values are provided in the literature (Table 2).

$$EP = ACR \cdot CV \quad (2)$$

where the following are defined: *EP*: Energy potential (MJ); *CV*: Calorific value (MJ kg^{-1}).

Residues are pruning wastes and pecan shells for the pecan trees and pruning wastes for peaches. Equation (4) calculates available biomass amount provided by pruning and adequate for peaches. Available biomass amount per tree values are calculated by using the data from the literature for pecan [34] and peaches [35]. Average yield of pecan is calculated as 20.4 kg per tree [37], and pecan shell ratio is 0.5 [38]. Equation (4) estimates the pecan shell biomass amount. Total biomass amount is then calculated by Equation (5).

$$AB = ABT \cdot TD \cdot PA \quad (3)$$

where the following are defined: *AB*: Available biomass (kg); *ABT*: Available biomass amount per tree (kg $tree^{-1}$); *TD*: Tree density (trees $acre^{-1}$); *PA*: Production area (acres).

$$PSB = AY \cdot 0.5 \quad (4)$$

where the following are defined: *PSB*: Pecan shell biomass (kg); *AY*: Average yield (kg $tree^{-1}$).

$$\textit{Total biomass}\ (\text{kg-}\textit{pecan}) = AB + PSB \quad (5)$$

Calorific values of pecan wastes are 8 MJ kg^{-1} for pruning wastes [34] and 20.06 (MJ kg^{-1}) for shells [39]. Energy potentials of pecan and peaches are calculated by Equation (2). The total waste and the total energy potential of annual crop residues were mapped using the GeoMedia 6.0 Software package.

Table 1. Residue-to-product ratios (RPR) provided by the literature.

		Corn		**Cotton**			**Rice**		**Oats**	**Peanuts**		**Sorghum**	**Soybeans**		**Sunflower**	**Wheat**	
		Stalk	***Cob***	***Stalk***	***Husk***	***Boll***	***Straw***	***Husk***		***Straw***	***Shells***		***Straw***	***Pods***		***Straw***	***Pod***
Arnott (2017)	[40]															1.3	
Ben-Iwo et al. (2016)	[20]	2.00	0.273	3.743			1.757	0.20		2.3	0.477	1.25	2.50	1.0			
Chen (2016)	[41]	1.00					1.50									1.50	
Ebadian et al. (2011)	[42]															1.30	
Einarsson and Persson (2017)	[43]	1.00							0.80						2.00	0.90	
Ericsson and Nilsson (2006)	[44]								1.30							1.30	
Graham et al. (2007)	[45]								2.00							1.70–1.30	
Hiloidhari et al. (2014)	[22]	2.00	0.30	3.80	1.10	1.10	1.50	0.20		2.00	0.30				3.00	1.50	0.30
Ji (2015)	[46]	2.00	0.20				1.00	0.25		1.14	0.30	1.60	1.50			1.17	
Jiang et al. (2011)	[24]	2.00		3.00			1.00									1.10	
Johnson et al. (2006)	[47]								1.40						1.50	1.20	
Kadam and McMillan (2003)	[48]	0.9–1.1															
Kahr et al. (2013)	[49]	1.00							1.10							0.80	
Kaltschmitt and Hartmann (2000)	[50]								1.20							0.80–0.90	
Koopmans and Koppejan (1997)	[51]						1.76		1.75							1.75	
Nelson (2002)	[52]	1.00														1.30–1.70	
Panoutsou and Labalette (2006)	[53]						1.00		1.27						1.40	1.00	
Perlack et al. (2005)	[54]	1.00											1.50–2.00				
Samuel (2015)	[55]	2.00	0.27	2.76			1.76	0.27								1.75	
Soriano et al. (2004)	[56]														2.61–2.97		
Summers et al. (2003)	[57]						0.81–2.30										
Walsh et al. (2000)	[58]	1.00														1.30–1.70	
Average		**1.38**	**0.26**	**3.33**	**1.10**	**1.10**	**1.44**	**0.23**	**1.35**	**1.81**	**0.36**	**1.43**	**1.88**	**1.00**	**2.25**	**1.30**	**0.30**

Table 2. Available crop residue ratios (%) and calorific values-lower heat value (MJ kg^{-1}) provided by the literature.

Available Crop Residue Ratios (%)																	
		Corn		**Cotton**			**Rice**		**Oats**	**Peanuts**		**Sorghum**	**Soybeans**		**Sunflower**	**Wheat**	
		Stalk	*Cob*	*Stalk*	*Husk*	*Boll*	*Straw*	*Husk*		*Straw*	*Shells*		*Straw*	*Pod*		*Straw*	*Pod*
Akdag (2007)	[59]	60	60	60	80	80	60	80	15	80	80		60		60	15	
Arnott (2017)	[40]															65	
Ben-Iwo et al. (2016)	[20]	70	100	100			100	100		50	100	80	100	100			
Jiang et al. (2011)	[24]	40.6					24.2									15.7	
Karaca (2015)	[21]	60	60	60					15		80				60	15	
Panoutsou and Labalette (2006)	[53]						60		50							50	
Average		**57.65**	**73.3**	**73.33**	**80**	**80**	**61.05**	**90**	**26.67**	**65**	**86.67**	**80**	**80**	**100**	**60**	**32.14**	

Calorific Values-Lower Heat Value (MJ kg^{-1})																	
		Corn		**Cotton**			**Rice**		**Oats**	**Peanuts**		**Sorghum**	**Soybeans**		**Sunflower**	**Wheat**	
		Stalk	*Cob*	*Stalk*	*Husk*	*Boll*	*Straw*	*Husk*		*Straw*	*Shells*		*Straw*	*Pod*		*Straw*	*Pod*
Akdag (2007)	[59]	18.5	18.4	18.2	15.65	15.65	16.7	12.98	17.4	20.74	20.74		19.40		14.20	17.90	
Arnott (2017)	[40]															17.94	
Ben-Iwo et al. (2016)	[20]	19.66	16.28	18.61			16.02	19.33		17.58	15.66	12.38	12.38	12.38			
Caslin, 2016	[60]															14.4	
Hiloidhari et al. (2014)	[22]	16.67	17.39	17.4	16.7	18.3	15.54	15.54		14.4	15.56		16.99		17.53	17.15	17.39
Karaca (2015)	[21]	18.5	18.4	18.2					17.4		20.7				17.4	17.90	
Panoutsou and Labalette (2006)	[53]						16.7		17.4							17.90	
Average		**18.33**	**17.62**	**18.10**	**16.18**	**16.98**	**16.24**	**15.95**	**17.40**	**17.57**	**18.17**	**12.38**	**16.26**	**12.38**	**16.38**	**17.20**	**17.39**

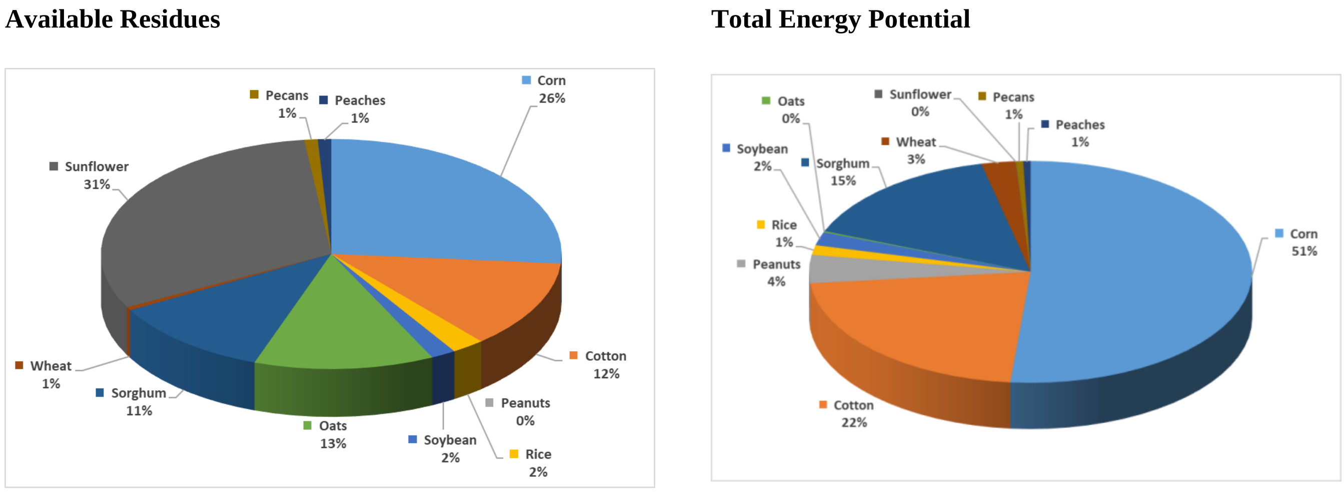
4. Results and Discussion

Three criteria were important for the calculation of the energy potential based on crop production in the region: residue-to-product ratios, availability ratios, and calorific values per kg. Tree density, biomass amount per tree, and calorific values are used to estimate the potential of tree products based on production area. Data from three different years (2007, 2012, and 2017) are gathered and analyzed (Figure 3) and added to the spatial database to provide further query possibility. An example can be seen in Figure 4 for 2012. The latest data for the 2017 were considered since there was no correlation between the years. Accordingly, the annual total average amounts were estimated for agricultural residues at 1.77 Mt, for available crop residues at 1.16 Mt, and for the heating value at 19.27 PJ. The average amount of residues, available residues that can be defined as obtainable from fields, and total energy potential for each product are given in Table 3.

Table 3. The calculated potential production of crop residues, available residues, and energy in the region (average—2017).

Crops	Residues (kt)	Available Residue (kt)	Total Energy Potential (PJ)
Corn	810.83	487.60	8.87
Cotton	309.00	234.79	4.10
Peanuts	63.43	43.51	0.77
Rice	25.19	16.38	0.27
Soybean	28.48	24.76	0.36
Oats	7.32	1.95	0.03
Sorghum	292.25	233.80	2.89
Wheat	83.78	26.93	0.46
Sunflower	0.71	0.42	0.01
Pecan	27.32	13.65	0.11
Peaches	0.24	0.12	0.01
Total	**1777.33**	**1160.08**	**19.27**

Considerable amounts of potential residues are provided by corn, cotton, and sorghum production. Thus, those crops have the highest share of potential available residue and energy production potential (Figure 3).



Available Residues

Total Energy Potential

Figure 3. The calculated share of available residues and total energy potential (%—2017).

A spatial database has been created for the further investigation purposes in terms of the Water, Energy, and Food Nexus. The average annual biomass potential that can be produced is mapped and shown in Figure 4 based on the counties of South-Central Texas Regional Water Planning Area for the year 2012.

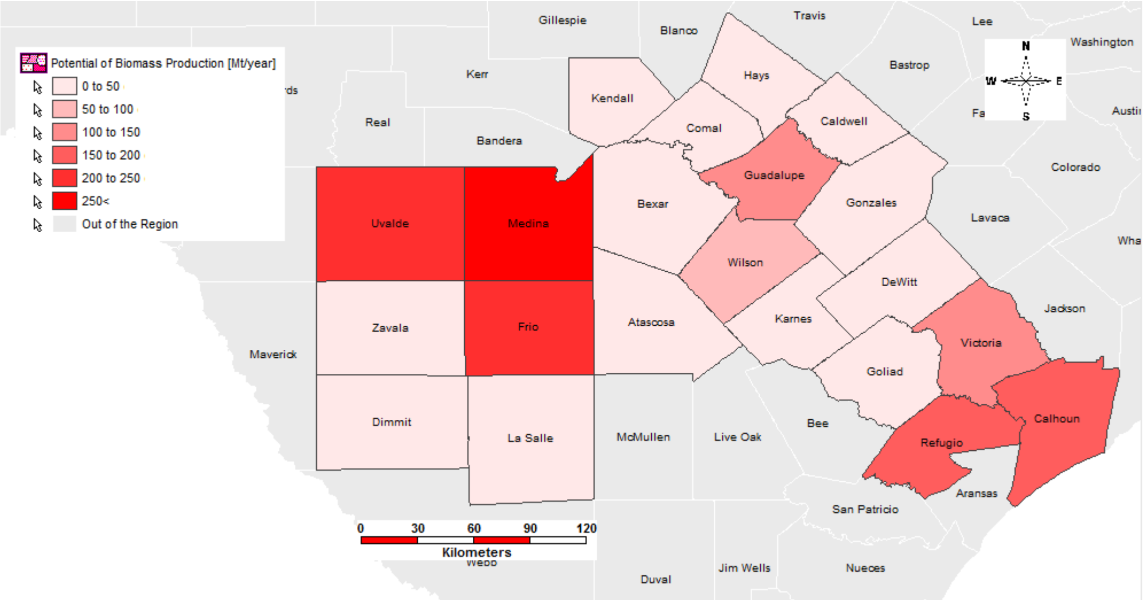


Figure 4. Example of generated maps to interpret the potentials. Average annual potential of biomass production (Mt—2012).

Calhoun, Medina, Uvalde, Victoria, Refugio, and Frio contributed to the available residue potential in 2007, Medina, Uvalde, and Frio have the highest potential in terms of available biomass and energy production that ran, and Victoria, Calhoun, and Refugio have slightly lower potentials in 2012. The residue amount has been increased in Victoria and decreased in the most of other counties in 2017, and thus, Victoria has the highest potential of bioenergy production (Figure 5a,b). This change was most likely due to the constantly changing profitability trends for agricultural production.

The potential production of utilizable agricultural wastes in 2017 is in the range of 898.7t kt–1421.39 kt for Region L. The average annual bioenergy value is estimated at 19.27 PJ, and ranges between 14.62 and 23.68 PJ. Tolessa (2023) [61] determined bioenergy potential of Ethiopia with same methodology within the range of 559–1144 PJ and the average as 836 PJ. Hiloidhari et al. (2014) [21] determined a 686 MT gross annual residue, of which 234 MT utilizable residue that equal to 4150 PJ in 28 states of India. Jiang et al. (2012) [23] states that the bioenergy potential of China is 7400 PJ/year, while Karaca (2015) [20] states that it is 268 PJ/year for Türkiye. Al-Hamamare et al. (2014) [24] determines the bioenergy potential of Jordan as 8.79 PJ, which is significantly lower than the potential of South-Central Texas.

Texas relies heavily on natural gas, coal, and nuclear power for most of its electricity, with the amounts of 16,344 GWh, 11,468 GWh, and 3790 GWh, respectively. The total non-renewable electricity generation is 31,602 GWh [13]. Toklu (2017) [18] estimates that biomass use in electricity generation will increase ten-fold in 2050 in comparison to 2009.

Considering only Region L, the average potential biomass-based electricity production could compensate for up to 16% of non-renewable electricity generated in Texas. In terms of a minimum–maximum range of potential electricity generation, the compensation potential changes between 12.6 and 20.2%.

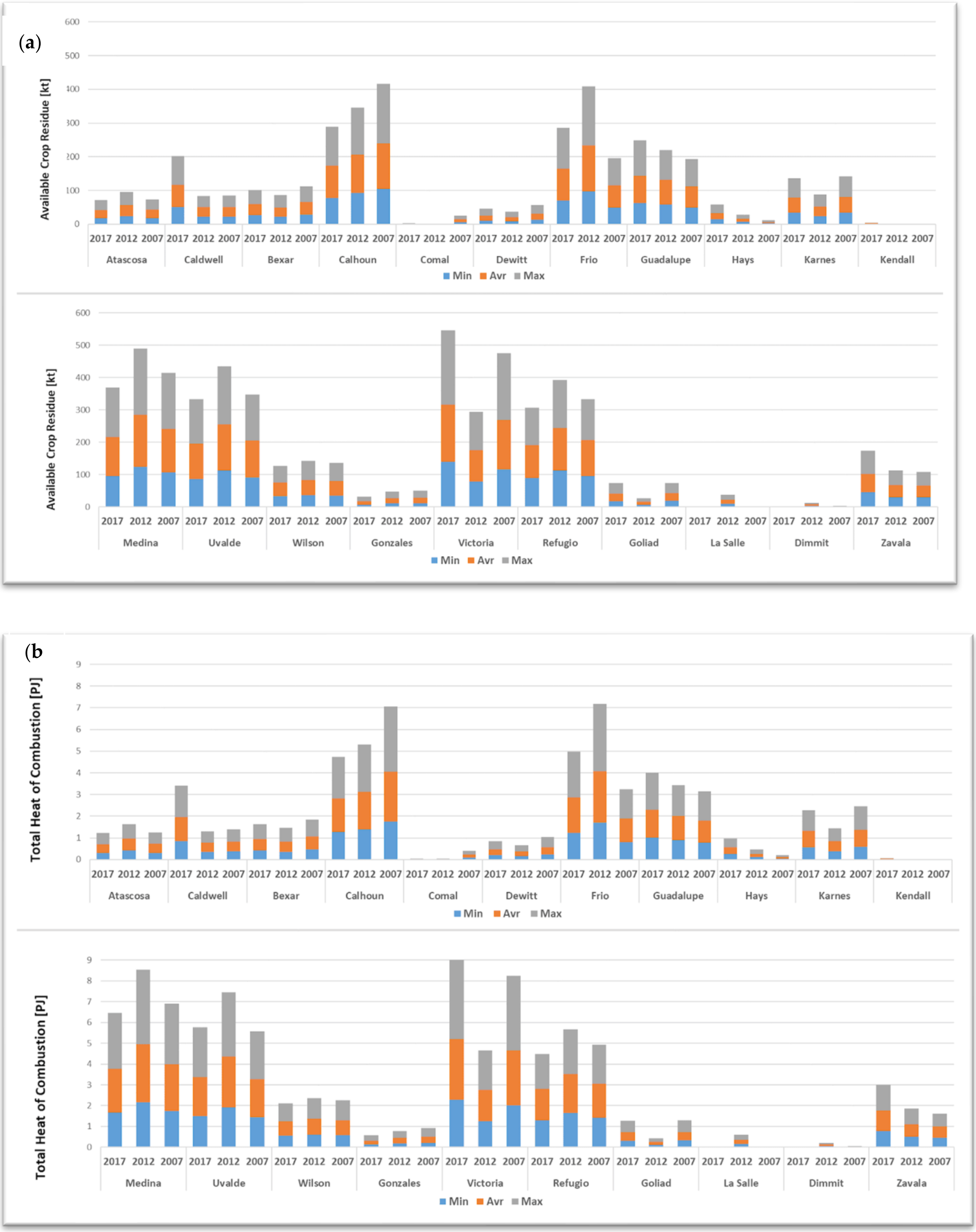


Figure 5. (**a**) Available crop residues for each county (max/min/avg). (**b**) Total calorific potential for each county (max/min/avg).

Numerous waste-to-energy transformation methods exist, such as gasification, anaerobic digestion, and the use of coal-fired boilers and power plants. Additionally, there are processes for converting biomass into ethanol and other transportation fuels. Depending on location, possible costs can diverse [62]. Combustion methods can generate roughly 90% of their energy from biomass, transforming it into various useful forms like hot air, water, steam, and electricity. The most basic form of this technology is a furnace that incinerates biomass in a combustion chamber. Electricity-producing biomass combustion plants, utilizing steam-driven turbines, have an efficiency rate of about 17–25%. However, this efficiency can soar to nearly 85% with cogeneration techniques. Enhancing efficiency and reducing emissions are key objectives. Interest is growing in wood-based heating and cooking appliances, including fireplaces, heat-storing stoves, pellet stoves, and central heating systems. Industrially, combustion systems vary and generally fall into categories like fixed-bed, fluidized bed, and dust combustion [19]. Mroue et al. (2019) [63] states that coal has the highest carbon footprint, although it is not the major contributor considering the electricity generation in Texas. Therefore, biomass resources can replace some of coal use.

Since the biomass can be a seasonable energy source [64], there are systems need to be analyzed for harvesting, storing, and transporting biomass efficiently, at a low cost [65]. Texas hosts 25 of 795 biomass power plants of US and 4 power plants are placed in Region L, which may reduce transportation costs significantly [12].

Besides the contributions to the energy production, utilizing agricultural wastes can improve the farms economically, which is one of the major aspects of sustainable agriculture [66,67]. Instead of producing energy crops as bioenergy sources that has transformed from food, utilizing the wastes of food production for the energy market will reduce the stress over scarcities of food, arable land, and water [29,68] together with the applications of low-impact development technologies (rainwater harvesting, bio retention basins, and permeable pavements) as new water sources for irrigation [69].

Three techniques are considered: rainwater harvesting (RWH), bio retention basins (BRB), and permeable pavements (PP). However, biomass amount can change with environmental factors and agricultural applications, as climate change, different water regime, fertilizer, or pruning applications [70,71], and bioenergy production is largely dependent on the availability of agricultural products. Therefore, proper governance is needed to introduce consistent regulatory strategies, which balance subsidies, tax credits, grants, mandates, and strong price-based policies for agriculture and energy [72,73]. In anticipation of future challenges, it is imperative to delve into the dynamic landscape of climate-resilient bioenergy strategies. Understanding the potential impacts of climate variability and change in bioenergy production will serve as a crucial foundation for devising proactive measures. By identifying resilient practices and adaptive technologies, we can fortify the bioenergy sector against the uncertainties posed by a changing climate. This exploration not only underscores the commitment to sustainable energy sources but also positions South Central Texas as a proactive hub for innovative and resilient bioenergy solutions, ensuring a steadfast contribution to renewable energy goals. The study by Knápek et al. emphasizes the dynamic nature of biomass potential, influenced by myriad factors including land availability, crop selection, and the impacts of climate change [74]. This perspective is particularly relevant to our study as it underscores the importance of considering temporal and environmental changes in biomass energy potential assessments. While the current analysis of this study provides a snapshot of biomass potential in Texas, the dynamic approach suggests that this potential is subject to change and must be regularly reassessed to remain accurate and relevant. The research conducted by Lozano-García et al. introduces a GIS-based modeling approach that combines a range of factors such as agricultural residue, infrastructure, and geographical constraints [75]. This comprehensive method facilitates a more detailed and localized assessment of biomass potential. Applying such a model to our context in Texas could potentially reveal more nuanced insights into the geographical distribution and feasibility of biomass energy production across different regions within the state. Both studies also highlight the importance of aligning biomass potential assessments with national energy policies and strategies. As it is considered the role of biomass in Texas's energy future, these studies remind us of the need to ensure that our findings and recommendations are in harmony with broader energy goals and socio-economic considerations. Furthermore, these studies emphasize the significance of accounting for limiting factors in biomass potential quantification. Legislative, technological, and economic constraints play a crucial role in determining the realistic potential of biomass as an energy source. This insight is crucial for our study as it guides us to consider similar constraints that might apply to the Texas context. While our study presents a specific analysis of biomass energy potential in Texas, integrating perspectives and methodologies from these advanced studies could enrich future research. A Water, Energy, and Food Nexus approach provide a more dynamic, detailed, and policy-aligned approach to biomass potential quantification, which is essential for the sustainable and efficient use of biomass as an energy resource (Table 4).

Table 4. SWAT (strengths, weaknesses, opportunities, and threats) analysis from a Water–Energy–Food (WEF) Nexus perspective.

WEF Nexus Component	Strengths (S)	Weaknesses (W)	Opportunities (O)	Threats (T)
Water	Food production already causes water consumption and abundant agricultural residues indicate a potential for water savings if they can be used instead of energy crops.	Dependence on climate conditions could still affect water availability for crop production.	Technological innovations like improved irrigation and precision agriculture could optimize water use.	Climate change poses a risk to water availability, potentially impacting biomass production.
Energy	The potential production of 898.7 t kt–1421.39 kt of agricultural waste can contribute significantly to Texas's energy portfolio.	Current heavy reliance on non-renewable energy sources and theoretical availability of residues can be different from reality.	Transition to bioenergy could enhance energy security and sustainability.	Fluctuating environmental factors and market dynamics could impact the stability of bioenergy supply.
Food	Crop diversification could lead to more efficient use of land and resources for both food and energy.	Crop rotation and agricultural production are sensitive to climate conditions.	Utilizing waste from agricultural products for bioenergy could foster socio-economic cooperation between agriculture and energy sectors.	Overemphasis on bioenergy crops might direct land and resource use for energy crops that compete with food production, leading to food security concerns.
Socio-economic	Potential transformation of waste into socio-economic benefits through energy sector collaboration.	Need for extensive research and development to stay ahead of emerging challenges.	Community engagement in bioenergy strategies can lead to inclusive and comprehensive sustainability approaches.	Potential resistance to change in traditional agricultural practices and energy production methods.
Governance	Supportive policy frameworks could promote the adoption of sustainable bioenergy practices.	Further interregional analyses are required for consistent decision making in agriculture and energy sectors.	Adaptive measures and supportive policies can facilitate the shift towards sustainable energy planning.	Lack of coordinated policies and strategies may lead to fragmented efforts and inefficiencies.

We emphasize the importance of drawing valuable insights from our experiences, with a specific emphasis on employing integrative endpoint metrics. These metrics should foster creativity and innovation by promoting synergies without introducing conflicts among our objectives. The achievement of one goal should not compromise the pursuit of sustainability objectives in other domains. Therefore, effective water governance necessitates a comprehensive consideration of diverse interests and perspectives within competing sectors, encompassing technological, political, environmental, and social dimensions [76].

Adaptive measures in the context of climate-resilient bioenergy strategies may include the following [77]:

1. **Crop Diversification:** Exploring and cultivating a variety of bioenergy crops that are climate resilient.

2. **Technological Innovations:** Developing and implementing advanced technologies and new methodologies that can adapt to fluctuating environmental factors, such as improved irrigation systems, precision agriculture, regenerative agriculture, or climate-smart agriculture.
3. **Risk Assessment and Management:** Conducting thorough assessments of climate-related risks to bioenergy production and implementing management plans to mitigate those risks.
4. **Research and Development:** Investing in ongoing research to stay ahead of emerging challenges and identify new technologies or practices that can enhance the resilience of bioenergy systems.
5. **Policy Frameworks:** Establishing supportive policies that encourage the adoption of climate-resilient practices within the bioenergy sector.
6. **Community Engagement:** Involving local communities and stakeholders in the planning and implementation of adaptive measures to ensure a comprehensive and inclusive approach.

5. Conclusions

Enhancing renewable energy portfolios is crucial to ensure the sustainability of energy since renewables are set to remain, by far, in the driving seat in forward thinking of energy security. Texas, as a leading energy producer in the United States, relies heavily on non-renewable sources. This study reveals that South Central Texas Regional Water Planning Area (Region L) has a considerable potential of contribution to transform energy portfolio of Texas into renewable way. In this study, an assessment of the currently available agricultural residues has been conducted, and the spatial distribution of crop residues in counties of Region L has been determined. Residue-to-product ratios and availability are used to estimate field crop residues; tree density and biomass amount per tree are used to estimate the residues of trees. Energy potential of residues is calculated by using heat values. The potential production of utilizable agricultural wastes is in the range of 898.7 t kt–1421.39 kt for Region L. The annual average bioenergy potential is estimated at 19.27 PJ, and ranged between 14.36 and 24.18 PJ in 2017. Non-renewable electricity generation of Texas can be compensated by bioenergy sources via the contribution of sixteen regions of Texas. Without ignoring the large dependence of bioenergy production on the availability of agricultural production that is sensitive to climate conditions, crop rotation and proper governance, further, interregional statewide analyses will increase the consistency of decisions to be made for the agriculture and energy sectors of Texas. If the utilization of waste from agricultural products as biomass in energy production increases, it may reveal the transformation of ignored waste into socioeconomic cooperation between the agriculture and energy sectors.

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