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Energy Potential of Agri Residual Biomass in Southeast Asia with the Focus on Vietnam

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Abstract: Southeast Asia currently faces a huge increase in energy consumption and serious environmental issues. A widely underutilized and still unexplored potential of these countries lies in residual biomass. In the present research, the production quantities and energy yields of the most abundant agricultural byproducts in Vietnam, i.e., rice straw, rice husks, sugarcane bagasse and sugarcane trash, were calculated. Total crop yield, residues ratio and net calorific values of the wet basis biomass served as input parameters for the calculations. Moreover, the results were found for individual regions and provinces of the country. The findings show that the production of paddy rice straw is an enormous 97 million tons per year with an energy potential of over 380 TWh, as well as another 9 million tons yearly and 35 TWh in the case of rice husks. More than half of rice biomass production is concentrated in the Mekong River Delta region. Harvesting and processing of sugarcane annually generates about 5 million tons of bagasse and over 3.5 million tons of sugarcane trash with the total energy potential of about 27 TWh, which is primarily available in the central regions of Vietnam. The detailed laboratory determination of fuel-energy properties of studied materials, such as gross and net calorific value, volatile matter, ash and moisture content and contents of chemical elements was also carried out. Based on the research results and literature analysis, the possibilities of biofuel production and energy utilization of the above-mentioned residues are discussed.

Keywords: agricultural waste; biomass production; biofuel; energy yield; calorific value; sustainable agriculture

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1. Introduction

Due to economic growth and an increase in population density, Vietnam faces a tremendous rise in energy consumption [1]. From being an energy exporter during 1990–2010, Vietnam has become dependent on energy import, although rising energy consumption was anticipated. Primary energy consumption in rural Vietnam relies strongly on biomass [2], representing the country's largest renewable energy source. Unfortunately, biomass is not treated adequately, and energy loss is enormous. Nearly half of the renewable energy used in 2017 was provided by modern bioenergy, which accounted for an estimated 12.4% of total final energy consumption. The remaining 81.6% of the energy supplied in Vietnam comes from coal, oil and natural gas, mostly imported into the country [3]. Vietnam is a young and fast-growing economy in Southeast Asia that has made efforts to tackle climate change issues internationally. Thus, a good understanding of the energy resources, markets, policies and scientific studies will help the country to move towards a cleaner and more sustainable economy [4].

The agricultural sector accounts for more than 15% of Vietnam's gross domestic product and concurrently for 40% of the country's labor force [5]. Table 1 shows the dominant crops that are cultivated in the country.

Table 1. Top six crops/commodities considering the total yearly yield in Vietnam.

	Production Quantity (t)
Crop	**Value**
Rice, paddy	44,046,250
Sugarcane	17,945,204
Vegetables, fresh	14,879,631
Cassava	9,847,074
Maize	4,874,054
Fruit, fresh	2,835,078

Source: Data from [6].

Based on Table 1, considering the vast production, which is also significantly associated with the generation of residual biomass, paddy rice and sugarcane were chosen as the main concern of this study.

As one of the most important cereals in Vietnam [7], rice farms have developed rapidly in recent decades. Between 1994 and 2017, rice production more than doubled [5], from 20 billion tons to more than 44 billion tons. The rice yield increased from 2.9 t ha^{-1} in 1990 to 5.8 t ha^{-1} in 2018, while the area of paddy rice plantations enlarged by only about 1.1% per year [5,8]. In the preceding decades, rice was collected manually, and the leftover biomass was suitable as a raw material for the paper industry, fertilizers and animal fodder. Nowadays, residue management in Vietnam has changed. Paddy rice on extensive commercial fields is collected by the new combine-based harvesting method, and the vast and increasing proportion of rice residues is left unused or commonly burned directly on the fields [7,9,10] with a negative environmental impact on the surroundings [7].

In the case of sugarcane, after the rapid increase of sugarcane production in Vietnam in the 1990s (see Figure 1), sugarcane production has practically not changed in the last two decades, varying from 14 to 20 million tons per year, with the highest production during 2013–2014. In 2018, almost 18 million tons of sugarcane were produced [11]. According to the Ministry of Agriculture and Rural Development of Vietnam [12], the trend is to continue stable production on up to 300,000 ha with increasing sugar output and quality. Sugarcane yields are high, about 70 t ha^{-1} (compared to about 1 t ha^{-1} for wheat, 2 t ha^{-1} for other grasses and 20 t ha^{-1} for trees) [13].

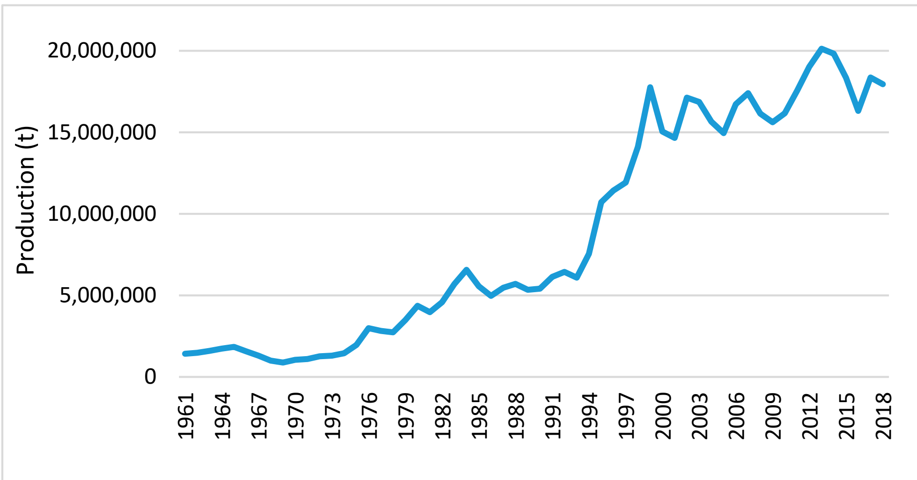

Figure 1. Sugarcane production in Vietnam [14].

Energy utilization of residual biomass seems to be an optimal solution for sustainable waste management and enhancing the country's energy security via local and renewable sources. Thus, this study's main objective was to investigate the energy potential as well as production quantities and fuel properties of the foremost biomass residues in Vietnam.

2. Materials and Methods

2.1. Secondary Data Analysis

Two types of data sources were used in this study. The main sources of secondary data were available scientific articles, Vietnamese governmental reports, statistical yearbooks, overviews and data from FAO. Secondary data sources contributed to the description and mapping of the current situation and possible energy applications of the studied residual biomass; it showed gaps in available information and served as input data for calculating the energy potential together with the results of the laboratory work.

2.2. Origin of Materials and Preparation of Analysis Samples

Based on the secondary data analysis regarding the biomass availability, the top three kinds of residual biomass materials (namely rice husks, rice straw and sugarcane bagasse) were collected in Vietnam during the 2019 spring season.

The rice husk is the agroindustrial residue characterized as the outermost layer of the paddy grain that is removed from the rice grains during the milling process [15,16]. Rice straw is described as an inedible fibrous plant material part left after the paddy rice harvesting process [17]. Both materials, rice husks and rice straw were gathered in the rural district Giao Thủy, located in the Nam Định Province of the Red River Delta region.

Sugarcane bagasse is the residue of processes leading to the extraction of sugarcane juice [18]. Sugarcane bagasse (from manual juice extraction) was collected on the local market of Bát Tràng village in Gia Lâm district of Hanoi.

For better visualization, the detailed Vietnam provinces' map is presented in Figure 2.

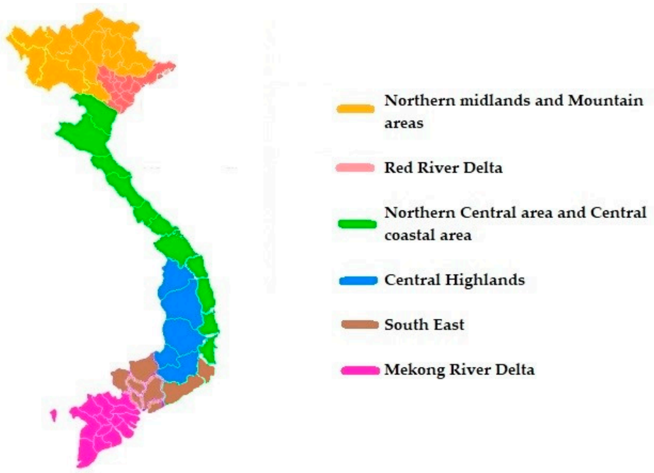

Figure 2. Map of Vietnam divided into provinces [19], adjusted by authors.

The representative material samples were obtained according to the standard sampling methodology BS EN ISO 18135:2017 [20]. For further laboratory testing, the analysis samples were prepared from the raw materials (not mixed with any other materials or additives) following the standard methodology of BS EN ISO 14780:2017 [21]. Laboratory knife mill Retsch Grindomix GM 100 (Retsch GmbH, Haan, Germany) was used for the final homogenization of the samples to the particle size below 1 mm.

2.3. Determination of the Biomass Energy Properties

A concise characterization of studied materials was carried out based on the latest European and International standards/International Organization for Standardization for solid biofuels.

Moisture Content. The measurement of moisture content was performed under the standard BS EN ISO 18134-3:2015 [22]. Prepared analysis samples were introduced into the drying oven Memmert 100–800 (Memmert GmbH, Schwabach, Germany) and dried at the temperature of 105 °C until a constant weight was obtained (for about 3 h). For each sample, the process was repeated n times until the difference between procedure n and $n-1$ stood equal or less than 0.2% absolute. The resulting moisture content was calculated as the mean of duplicate determinations using the following equation:

$$M_{ar} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \quad (1)$$

where: M_{ar}—moisture content as received, wet basis, %; m_1—mass of an empty dish and lid, g; m_2—mass of a dish and lid with a sample before drying, g; m_3—mass of a dish and lid with a sample after drying, g.

Volatile Matter Content. Content of volatile matter was determined according to BS EN ISO 18123:2015 standard [23] as the loss in mass when the analytical sample placed in a crucible was heated at 900 °C for 7 min. For the sample heating, a muffle furnace ELSKLO MP5 (Elsklo Ltd., Desná v J·h, Czech Republic) was applied. The content of volatile matter in the samples was calculated based on the following equation, and the final result was reported as the mean of duplicate determinations with respect to a repeatability precision:

$$VM = \frac{m_2 - m_3}{m_2 - m_1} \times 100 \quad (2)$$

where: VM—volatile matter on a dry basis, %; m_1—mass of the empty crucible and lid, g; m_2—mass of the crucible with measured sample and lid before heating, g; m_3—mass of the crucible with measured sample and lid after heating, g.

Non-volatile Matter Content or Fixed Carbon. Fixed carbon is a remainder after the percentages of total moisture, ash, and volatile matter subtracted from 100% based on BS EN ISO 16559:2014 [24]. For better comparison, the moisture content was excluded, and fixed carbon was calculated as [25]:

$$FC = 100 - VM - A \quad (3)$$

where: FC—fixed carbon on a dry basis, %; VM—volatile matter on a dry basis, %; A—ash content on a dry basis, %.

Ash content, a mass of inorganic residue remaining after sample heating under specific conditions, was determined according to the standard BS EN ISO 18122:2015 [26]. Approximately 1 g of analysis sample, which had been previously dried at 105 °C, was placed in a muffle furnace LAC LH 06/13 (LAC, Rajhrad, Czech Republic) and heated from an ambient temperature to 250 °C, for 30 min and then retained at this temperature for a further 60 min. Afterwards, the temperature inside the furnace was uniformly raised to 550 °C over 30 min and kept at this level for the other 120 min. The equation for the calculation of ash content is presented below. Ash content of each sample was found as a mean of three repetitions taking into account a repeatability precision.

$$A = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \quad (4)$$

where: A—ash content on a dry basis, %; m_1—mass of an empty dish, g; m_2—mass of dish with a sample, g; m_3—mass of dish with ash, g.

Determination of Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S), Chlorine (Cl) and Oxygen (O) Content. C, N and H content determination was performed per the standard BS EN ISO 16948:2015 [27] using the laboratory automatic device LECO CHNS628 (LECO Corporation, Saint Joseph, MI, USA). Calibration of the analyzer was undertaken beforehand, then 0.1 g of dried analysis samples wrapped in aluminum foil and prepared in three replicates was placed into the equipment and combusted to oxidize the sample into simple compounds that were then detected with thermal conductivity and infrared detectors (at 100% oxygen and temperature around 1050 °C). The results were calculated automatically and expressed as % by mass.

Content of S and Cl was determined by following the standard BS EN ISO 16994:2016 [28], where S content was measured via the combustion method in the Sulphur add-on module to the Elemental Determinator LECO CHN628 Series and the Cl content was determined by the titrimetry technique.

O content was calculated by difference:

$$O = 100 - C - H - N - S - Cl - A \tag{5}$$

where: O—oxygen content on a dry basis, %; C—carbon content on a dry basis, %; H—hydrogen content on a dry basis, %; N—nitrogen content on a dry basis, %; S—sulphur content on a dry basis, %; C—chlorine content on a dry basis, %; A—ash content on a dry basis, %.

Calorific Value. Calorific value was determined under the standard BS EN ISO 18125:2017 [29]. Around 1 g of the material compressed in an unbreakable test piece was placed into the calorimeter IKA 6000 (IKA-Werke GmbH & Co. KG, Staufen, Germany), which was configured with the required information such as sample weight, hydrogen content, etc. Gross calorific value (GCV) was then measured automatically, and net calorific value (NCV) was calculated according to the following equation:

$$Q = Q_{gr} - 24.42\ \times (M + 8.94\ \times H) \tag{6}$$

where: Q—net calorific value, J·g^{-1}; Q_{gr}—gross calorific value, J·g^{-1}; 24.42—coefficient corresponding to 1% of the water from the sample at 25 °C; M—moisture content in the sample, %; 8.94—coefficient for the conversion of hydrogen to the water; H—hydrogen content in the sample, %.

2.4. Calculation of the Total Energy Yield

The equation for the energy potential/energy yield of residual biomass was designed following the methodology of Akhmedov et al. [30]:

$$Ep = (Tp * k) * Q \tag{7}$$

where: Ep—annual energy potential of residual biomass, TJ; Tp—total annual grain/crop production of country/region/province, t; k—constant/share of residual biomass or residue ratio, where:

- Constant for rice straw is 2.2, and it has been calculated as an average value of rice straw residues according to previous studies [15,31];
- Constant for rice husks is 0.2, the value was obtained from the previous studies [15,32];
- Constant for sugarcane bagasse is 0.3, the value was gained from previous publications [33,34];
- Constant for sugarcane trash is 0.2, the value was extracted from the previous studies [35,36].

Q—net calorific value of residual biomass as received*, TJ t^{-1}.

* as the value for sugarcane trash was not tested in the laboratory within the frame of this study, thus, the Q equal to 11.6 MJ kg^{-1} (0.0116 TJ t^{-1}) at moisture content 30% was taken into consideration according to De Beer [37].

The obtained results of energy potential were also converted and expressed in another unit, i.e., TWh as 1 TWh is equal to 3600 TJ.

3. Results and Discussion

3.1. Availability of Paddy Rice Residual Biomass and Possibilities of Energy Use

Table 2 shows the division in paddy rice production through regions and provinces in Vietnam. It is visible that the most productive region is the Mekong River Delta, with a production of over 24 million tons per year. Table 2 highlights provinces from every region with the highest production and the top five provinces by the production across Vietnam.

Table 2. Paddy rice production in Vietnam in 2018.

Production of Paddy by Regions and Provinces (t)												
Region	**Red River Delta**	**6,298,000**	**Northern Middlands and Mountain Areas**	**3,382,800**	**Northern Central Area and Central Coastal Area**	**7,059,600**	**Central Highlands**	**1,379,800**	**Mekong River Delta**	**24,506,900**	**South East**	**1,418,900**
Province	Ha Noi	1,024,600	Ha Giang	212,800	**Thanh Hoa**	**1,413,500**	Kon Tum	91,600	Long An	2,802,600	Binh Phuoc	42,600
	Ha Tay	no data	Cao Bang	132,500	Nghe An	1,009,100	Gia Lai	362,100	Tien Giang	1,254,500	**Tay Ninh**	**813,000**
	Vinh Phuc	330,600	Bac Kan	114,700	Ha Tinh	535,300	**Dak Lak**	**697,500**	Ben Tre	236,700	Binh Duong	29,100
	Bac Ninh	410,400	Tuyen Quang	262,400	Quang Binh	284,700	Dak Nong	78,700	Tra Vinh	1,268,000	Dong Nai	325,300
	Quang Ninh	208,600	Lao Cai	172,900	Quang Tri	275,500	Lam Dong	149,900	Vinh Long	969,500	Ba Ria—Vung Tau	129,800
	Hai Duong	702,500	Yen Bai	210,000	Thua Thien-Hue	334,400			Dong Thap	3,330,200	Ho Chi Minh city	79,100
	Hai Phong	440,800	Thai Nguyen	386,400	Da Nang	31,900			An Giang	3,926,900		
	Hung Yen	415,400	Lang Son	205,200	Quang Nam	462,600			**Kien Giang**	**4,267,400**		
	Thai Binh	**1,030,400**	**Bac Giang**	**599,500**	Quang Ngai	440,200			Can Tho	1,426,300		
	Ha Nam	386,300	Phu Tho	365,800	Binh Dinh	666,500			Hau Giang	1,246,100		
	Nam Dinh	891,200	Dien Bien	185,300	Phu Yen	392,200			Soc Trang	2,132,700		
	Ninh Binh	457,200	Lai Chau	143,800	Khanh Hoa	261,100			Bac Lieu	1,115,300		
			Son La	184,300	Ninh Thuan	243,300			Ca Mau	530,700		
			Hoa Binh	207,200	Binh Thuan	709,300						
WHOLE COUNTRY 44,046,000												

Note: Top 5 provinces by production ; Bold font—Top in a region; Source: Data from [8,38].

The rice harvesting process generates two main types of agricultural residues: rice straw and rice husks. Nowadays, this type of biomass is neglected regarding its potential as raw material or material suitable for energy use [5,15]. Moreover, rice straw and rice husks are the most unutilized parts of the crop. The high mineral content makes crop residues unsuitable as animal feed. However, high lignocellulose content underscores the potential of paddy rice residues as prospective energy sources [39].

The harvested area of paddy rice in Vietnam is around 7.5 million ha [9,39]. According to Lim et al. [31] and Pode [15], the residual biomass in the form of rice straw generated from rice harvesting can range from 0.41 to 3.96 kg per kg of paddy rice harvested. Furthermore, Matías et al. [39] stated that out of a 19.4 t ha^{-1} total biomass yield of paddy rice, on average, about 9.7 t ha^{-1} is the proportion of rice straw, i.e., one half. In addition, for Satlewal et al. [9], 1.5 tons of rice straw is generated per ton of rice. However, Jeng et al. [40] clarified that the weight of rice straw varies with the rice variety and further depends on crop height, number of leaves and greens, the thickness of straw, planting method and soil properties. Rice straw as an energy feedstock has an advantage in produced volume, and it is also a silica-rich material [8,9,39]. However, as mentioned earlier, rice straw is currently an untapped resource in Vietnam, the usual practice is indiscriminate and open burning of the straw in the fields [5,9,41]. The consequence of uncontrolled burning is the emission of trace gases and aerosols that leads to air pollution [17].

Generally, the appropriate procedure to obtain energy from rice straw biomass is through different combustion processes (direct combustion, pyrolysis, gasification) [15]. Still, there are many challenges in the transformation of raw biomass material into biofuel. Therefore, storage, transportation and operation issues have to be solved properly. Moreover, the straw collection is also problematic as the harvest time affects the availability of material [15,39]. Since rice straw is produced in a dispersive manner that is difficult to use directly as biofuel, this biomass material demands densification technology to ease transportation, storage and handling process, leading to denser solids (pellets, briquettes, or sticks) with tremendously higher energy intensity [41]. Production of the rice straw biofuels is accompanied by two technical challenges: high energy consumption during the densification process (up to 90 kWh t^{-1} for rice straw pelleting process) and relatively low calorific value [42]. In addition, according to Sharma et al. [43], rice straw is not the best material for energy utilization due to its calorific value; on the other hand, this material is accessible in vast amount, and with appropriate pretreatment, production of rice straw biofuel is worthwhile, e.g., to produce quality solid biofuel it is crucial to modify the recalcitrant nature of rice straw through the alterations in the interactions of cellulose, hemicellulose and lignin, enhancing the accessibility of cellulose, removing the lignin-carbohydrates complexes and decreasing the crystallinity of cellulose. Table 3 shows various possible pretreatment methods used in previous studies.

Table 3. Pretreatment methods for rice straw biofuels.

Pretreatment Method	Compound	Advantages	Disadvantages	Reference
Chemical	Dilute acid	Cost-effective Increase yield	Expensive acid Corrosion-resistant equipment	[44]
	Alkali	Efficient removal of lignin	Expensive alkali catalyst	[45]
	Ionic liquids	Mild processing conditions	Expensive chemicals	[46]
Physico-chemical	Steam explosion	Eco-friendly approach Eco-friendly approach	The bulk requirement of energy and water	[47]
Physical	Extrusion	Reduction in crystal nature of cellulose	Not cost-effective	[44]
	Microwave	Better yield	Expensive	[45]
	Milling	Reduction in size and degree of crystallinity	More consumption of power and energy	[44]

As distinct from rice straw, rice husks come with numerous advantages—husks are typically collected at the factory level, very dry and with very low moisture content, not requiring preprocessing [16]. Nowadays, rice husks are widely applied as bedding in the animal husbandry industry, mainly for poultry litter [48]. Globally, in the field of bioenergy, a common procedure to obtain energy from rice husks is using thermochemical processes as direct combustion, pyrolysis, gasification and liquefaction [49]. Various authors [50–53] identified pyrolysis as the most promising and effective method to obtain energy and create products like bio-char, bio-oil and pyrolysis gas. Manatura et al. [54] presented an exergy analysis of combined torrefaction and gasification process on rice husks pellets.

3.2. *Availability of Sugarcane Residual Biomass and Possibilities of Energy Use*

The most important sugarcane producing regions in Vietnam could be seen in Table 4. As also mentioned by Bhattacharyya and Thang [55], they are Central Highlands, Northern Central area and Central Coastal area. Production is according to the distribution of mills across Vietnamese districts (Figure 3). Based on Doanh [56], there are 36 mills under operation in total. This number decreased in recent years. Fourteen mills are located in the Central Highlands region and 11 mills are in the Northern Central area and Central Coastal area region. By MARD [12], the sugarcane industry met numerous difficulties in recent years. Recently, 17 of 36 factories faced the risk of equity, and the problem arose as a result of the importation of cheap sugar from abroad.

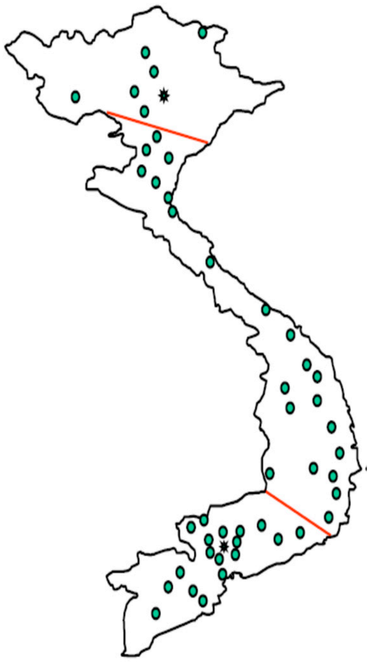

Figure 3. Distribution of sugar mills in Vietnam [57].

Table 4. Sugarcane production in Vietnam in 2018.

Production of Sugarcane by Regions and Provinces (t)												
Region	**Red River Delta**	**105,757**	**Northern Midlands and Mountain Areas**	**2,105,331**	**Northern Central Area and Central Coastal Area**	**6,343,687**	**Central Highlands**	**3,942,434**	**Mekong River Delta**	**3,335,210**	**South East**	**1,985,158**
Province	Ha Noi	1751	Ha Giang	23,652	Thanh Hoa	1,700,627	Kon Tum	84,890	Long An	480,878	Binh Phuoc	6984
	Ha Tay	no data	Cao Bang	227,336	Nghe An	1,517,114	**Gia Lai**	**2,577,719**	Tien Giang	11,412	**Tay Ninh**	**1,132,009**
	Vinh Phuc	4050	Bac Kan	5711	Ha Tinh	8350	Dak Lak	1,251,331	Ben Tre	59,190	Binh Duong	23,791
	Bac Ninh	676	Tuyen Quang	535,530	Quang Binh	3300	Dak Nong	4,740	Tra Vinh	454,484	Dong Nai	787,680
	Quang Ninh	25,084	Lao Cai	9295	Quang Tri	2459	Lam Dong	23,754	Vinh Long	14,681	Ba Ria-Vung Tau	14,002
	Hai Duong	2827	Yen Bai	12,333	Thua Thien-Hue	4789			Dong Thap	1994	Ho Chi Minh city	20,692
	Hai Phong	3893	Thai Nguyen	9126	Da Nang	no data			An Giang	395		
	Hung Yen	45	Lang Son	8451	Quang Nam	9562			Kien Giang	367,307		
	Thai Binh	4747	Bac Giang	9946	Quang Ngai	166,183			Can Tho	no data		
	Ha Nam	no data	Phu Tho	18,553	Binh Dinh	66,787			**Hau Giang**	**1,039,337**		
	Nam Dinh	4278	Dien Bien	1368	**Phu Yen**	**1,738,111**			Soc Trang	843,587		
	Ninh Binh	**58,406**	Lai Chau	6358	Khanh Hoa	865,051			Bac Lieu	17,365		
			Son La	**621,765**	Ninh Thuan	201,300			Ca Mau	44,580		
			Hoa Binh	615,907	Binh Thuan	60,054						
WHOLE COUNTRY 17,945,500												

Note: Top 5 provinces by production; Bold font—Top in a region; Source: Data from [11,38].

Sugarcane produces two main types of residues: sugarcane bagasse and sugarcane trash. Bagasse represents up to 30% of sugarcane weight [18]. One way to use sugarcane bagasse is for energy production. Bagasse can be burned as raw material, with no specific processing. Very often, directly from the sugar mill, bagasse is fed into the boiler. However, in this case, its calorific value is very low [58]. By Brunerová et al. [59], bagasse in the form of briquettes presents a much better energy source with high calorific value and other positive indicators. Moreover, Bhattacharyya and Thang [55] have stated that improving heat and power production is an attractive option to meet energy demands in Vietnam. Furthermore, one solution is to enhance the energy production in sugar mills via an increase in the calorific value of processed bagasse (dried and transformed into briquettes). According to Kanwal et al. [60], the torrefaction of bagasse is also considered due to the improvement of energy production characteristics. Thus, the higher calorific value offers the opportunity to produce more energy than factories require, and the rest of the energy will be sold out. In terms of the entire sugar industry in Vietnam, this solution could help national energy security.

The second residue is sugarcane trash, i.e., biomass, which is left on the field after harvesting, and it consists of green leaves, dry leaves, sheaths, tops, stalk fractions and physical mineral impurities [61]. The average production of sugarcane trash is estimated to be 14 tons per ha (20%) [62]. Normal practice is to windrow and burn this biomass in the field [36]. According to Rípoli et al. [33], the most promising usage of sugarcane trash is as a fuel for direct energy production or as a part of feedstock for second-generation biofuels. In addition, Nakashima et al. [63] highlighted that for the right and sustainable utilization of trash, appropriate handling at the beginning is always important. Hand-in-hand with the harvesting of the demanded crop, it is required to take proper care of trash, raking and baling, leading to a better collection of waste with low amounts of soil contaminants that can affect it as a source. These highlights the seeming underutilization of sugarcane trash as a potential energy source.

3.3. Evaluation of Fuel-Energy Properties of Tested Biomass Materials

Table 5 summarizes the research results indicating the main properties of tested materials.

Table 5. Physical and chemical properties of rice straw, rice husks and sugarcane bagasse.

Parameters	Units	Material		
		Rice Straw	**Rice Husks**	**Sugarcane Bagasse**
Moisture, M	wt.% ar	13.76	9.14	32.14
Volatile matter, VM	wt.% d	73.65	70.78	72.41
Non-volatile matter Fixed carbon, FC	wt.% d	15.98	15.43	15.72
Ash, A	wt.% ar	8.94	12.53	8.08
Ash, A	wt.% d	10.37	13.79	11.91
Carbon, C	wt.% d	44.90	43.89	45.19
Hydrogen, H	wt.% d	5.56	5.43	6.08
Nitrogen, N	wt.% d	0.80	0.91	1.30
Sulphur, S	wt.% d	0.23	0.09	0.02
Chlorine, Cl	wt.% d	0.04	0.03	0.06
Oxygen, O	wt.% d	38.10	35.86	35.44
Net calorific value, Q	MJ kg^{-1} ar	14.15	14.45	10.40
Net calorific value, Q	MJ kg^{-1} d	16.80	16.15	16.47
Gross calorific value, Q_{gr}	MJ kg^{-1} ar	15.53	15.74	12.07
Gross calorific value, Q_{gr}	MJ kg^{-1} d	18.01	17.33	17.80

ar—as received, d—dry basis, wt.%—percentage by weight.

Table 5 shows that the properties of dried materials are similar and common for herbaceous biomass. All materials are characterized by high ash content, which was found to be the highest in the case of rice husks, and relatively low calorific values, the lowest in the case of husks, too.

Compared to other studies, several authors have published even higher values of ash content in rice husks, e.g., 20.26% for dry biomass [31] or up to 25.32% of ash was measured in the rice husks with the moisture content of 6.03% originated from Australia [49]. The husk gross calorific value 15.84 MJ kg^{-1}, stated by Jenkins et al. [64], corresponds to the measured gross calorific value as received (see Table 5). According to Weldekidan et al. [49], rice husks compositional analysis is as follows: 20–35% cellulose, 15–30% hemicellulose and up to 10% lignin.

Other studies also confirmed high ash content in rice straw biomass: 13.13% of ash in rice straw from China with moisture content 13.40% [65], 15.94% in rice straw from the US [66], 16.11% dry in Cambodia [67] and 18.67% dry ash content [31]. Again, the values mentioned above are even higher compared to those from Vietnam. The gross calorific value of the rice straw was also found by various authors: 14.7. MJ kg^{-1} [41], 15 MJ kg^{-1} [42], 15.3 MJ kg^{-1} [15] and 16 MJ kg^{-1} [43]. The gross calorific value as received determined in the present research is in this range. For comparison, according to Pietka et al. [68] gross calorific value of wooden biomass is about 19 MJ kg^{-1} and 17 MJ kg^{-1} for fibrous biomass of hemp [69]. By Nguyen et al. [5], the rice straw ash and the ash of rice husks [15] is rich in silica, a desirable component in different industries, including power plants. Compositional rice straw analysis is as follows: 39.04% cellulose, 20.91% hemicellulose and 5.71% lignin [43].

For sugarcane bagasse, in contrast, previous studies from different countries like Iran, Phillippines or Brazil have mentioned lower content of ash, as 1.7–4.8% [70], 2.3–6.2 [71] and 6.5 [72], respectively. According to Kumar and Kumar [58] typical gross calorific value of wet sugarcane bagasse after juice extraction is only 8.4 MJ kg^{-1} (at 53.28% moisture content), and it significantly increases after moisture reduction, e.g., 15 MJ kg^{-1} (at 19.76% of moisture). This fact was also confirmed by Brunerová et al. [59], with the gross calorific value of dried and densified bagasse of 18.35 MJ kg^{-1} and the net calorific value of 17.06 MJ kg^{-1}. In general, sugarcane bagasse consists of approximately 50% cellulose, 25% hemicellulose and 25% lignin, but the composition of bagasse is influenced by several factors such as the method of harvesting (manual or mechanical), use of fire for straw removal and type of soil where sugarcane was planted [58].

Regarding sugarcane trash, Szczerbowski [72] declared that there is 6.2% of ash in its chemical composition. Based on the practical study of Woytiuk [35], the ash content of sugarcane trash varied between 9 and 12%. In addition, De Beer [37] stated that within 2–3 days of drying in the fields, the moisture content in the trash dropped to 30% and 15% within two weeks. The calorific value of sugarcane trash at 10% moisture content is about 15.8 MJ kg^{-1}. According to Woytiuk [35], the calorific value on a dry basis range between 17.07 and 18.32 MJ kg^{-1}. Table 5, therefore, shows that the results of sugarcane bagasse are similar to the above-mentioned values of ash content and calorific value characteristic for sugarcane trash.

3.4. Estimation of Energy Potential

3.4.1. Energy Potential of Paddy Rice Residual Biomass

Table 6 below presents energy potential and generated quantities of rice straw and rice husks in the whole of Vietnam as well as its distribution over the regions. The results of the calculations are based on available secondary data (i.e., data on annual crop production and residues ratio) and the results of the laboratory tests (net calorific value of residual biomass as received).

Table 6. Production quantity and energy yield of paddy rice residual biomass in Vietnam per year.

Region	Rice Straw			Rice Husks		
	Production (t)	Energy Potential		Production (t)	Energy Potential	
		(TJ)	(TWh)		(TJ)	(TWh)
Mekong River Delta	53,915,180	762,900	211.92	4,901,400	70,825	19.67
Northern Central area and Central coastal area	15,531,120	219,765	61.05	1,411,920	20,402	5.67
Red River Delta	13,855,600	196,057	54.46	1,259,600	18,201	5.06
Northern midlands and Mountain areas	7,442,160	105,307	29.25	676,600	9776	2.72
South East	3,121,580	44,170	12.27	283,800	4101	1.14
Central Highlands	3,035,560	42,953	11.93	275,960	3988	1.11
Vietnam	**96,901,200**	**1,371,152**	**380.88**	**8,809,200**	**127,293**	**35.36**

With regards to residues, there is still a significant lack of data about its availability and produced quantities. The review by Lim et al. [31] summarized the estimated data of paddy rice residue production on different continents. Furthermore, it showed the gap of information in the case of individual countries, e.g., Vietnam. According to recent publications [8,9], it was predicted that about 72.7 million tons of rice straw could be available for energy purposes in Vietnam. This number is lower than the quantity calculated in this study, probably due to the increased paddy yields during the years or bigger residue ratio, which was taken into account, or reduction in postharvest straw losses. However, another current study [16] stated that approximately 8.55 million tons of rice husks were generated in Vietnam in 2018, which corresponds to our calculations.

Table 6 shows that the potential of energy stored in rice straw and rice husks considering its vast production is massive. Furthermore, it illustrates that the energy potential in husks can be 11 times as much in straw. The average estimated household energy consumption in Vietnam is 4492 kWh annually, where 74% is electricity consumption and 26% is the energy needed for cooking (liquefied petroleum gas) [73]. It implies that the full capacity of residual biomass from paddy rice could theoretically cover the energy needs of over 92 million households.

The highest energy potential of paddy residues lies in the Mekong River Delta region (around 230 TWh), which accounts for more than half of the entire country's potential. From rice straw biomass only, the Mekong River Delta could supply up to 47 million households in the region with energy for a year. Overall, the five top provinces with the most extensive availability and energy potential of rice straw and rice husks are located in the Mekong River Delta region (see Table 7). The most productive province is Kien Giang, with over 40 TWh per year, greater than that in some regions in Vietnam (like Northern midlands and Mountain areas region, South East, Central Highlands).

Table 7. Annual paddy rice biomass production and energy potential by top provinces.

Province	Rice Straw			Rice Husks		
	Production (t)	Energy Potential		Production (t)	Energy Potential	
		(TJ)	(TWh)		(TJ)	(TWh)
Kien Giang	9,388,280	132,844	36.90	853,480	12,333	3.43
An Giang	8,639,180	122,244	33.96	785,380	11,349	3.15
Dong Thap	7,326,440	103,669	28.80	666,040	9624	2.67
Long An	6,165,720	87,245	24.23	560,520	8100	2.25
Soc Trang	4,691,940	66,391	18.44	426,540	6164	1.71

The Northern Central area and Central coastal area region has the second-highest energy yield of residual rice biomass in Vietnam (almost 67 TWh in total), followed by the

Red River Delta region (around 60 TWh). The calculated energy yield of the former and the latter is equal to the yearly energy supply for nearly 15 and over 13 million households, respectively. Together the potential of both regions makes approximately half the potential of the Mekong River Delta region (see Table 6).

The Northern midlands and Mountain areas region is the fourth-largest producer of rice residues, followed by the South East region and the Central Highlands that are both the least producers (just above 13 TWh each) with their total energy potential of rice residues more than 17 times smaller in comparison with the Mekong River Delta region. Nevertheless, both regions could still theoretically supply around 5 million households with energy from rice straw biomass and 500 thousand households with the energy capacity from rice husks annually.

3.4.2. Energy Potential of Residual Sugarcane Biomass

Production of sugarcane in Vietnam is lower than paddy rice; however, the residual biomass still has significant energy potential. A comparison of the results shows that the energy yield of residues from rice is approximately 15 times higher than the total yield of sugarcane residues. Table 8 below illustrates the availability and the energy potential of sugarcane bagasse and sugarcane trash divided into regions of the country.

Table 8. Production quantity and energy yield of residual sugarcane biomass in Vietnam per year.

Region	Sugarcane Bagasse			Sugarcane Trash		
	Production (t)	Energy Potential		Production (t)	Energy Potential	
		(TJ)	(TWh)		(TJ)	(TWh)
Northern Central area and Central coastal area	1,903,106	19,792	5.50	1,268,737	14,717	4.09
Central Highlands	1,182,730	12,300	3.42	788,487	9146	2.54
Mekong River Delta	1,000,563	10,406	2.89	667,042	7738	2.15
Northern midlands and Mountain areas	631,599	6569	1.82	421,066	4884	1.36
South East	595,547	6194	1.72	397,032	4606	1.28
Red River Delta	31,727	330	0.09	21,151	245	0.07
Vietnam	**5,383,650**	**55,989.96**	**15.55**	**3,589,100**	**41,633.56**	**11.56**

Results show that the total energy potential of sugarcane biomass in Vietnam is more than 27 TWh. This amount of energy could cover the energy consumption of about 6 million households, with the share of bagasse only 1.3 times greater than that of sugarcane trash.

The Northern Central area and Central coastal area region has the highest energy potential (nearly 9.6 TWh in total) due to the extensive cultivation of sugarcane, followed by the Central Highlands and the Mekong River Delta regions. The Mekong River Delta region has almost twice as low energy potential as the topmost region. The total calculated energy potential of residual sugarcane biomass in the Northern Central area and Central coastal area region makes up one-third of the entire country, and it is equivalent to the yearly energy consumption of over 1.2 million households in case of bagasse and below 1 million households for sugarcane trash.

Subsequently, Northern midlands and Mountain areas and the South East regions together represent only about 20% of the country's energy potential. The minor production of sugarcane and thus the smallest energy yield of residual biomass lie in the Red River Delta region (only 0.16 TWh totally). Here, however, the energy stored in sugarcane residues could still satisfy the energy needs of more than 35 thousand households.

Table 9 presents the energy potential of sugarcane bagasse as well as sugarcane trash in the top five producing provinces. Gai Lai and Dak Lak are situated in the Central Highlands region, and the rest of the provinces are located in the Northern Central area and central Coastal area region.

Table 9. Annual sugarcane residual biomass production and energy potential by top provinces.

Province	Sugarcane Bagasse			Sugarcane Trash		
	Production (t)	Energy Potential		Production (t)	Energy Potential	
		(TJ)	(TWh)		(TJ)	(TWh)
Gia Lai	773,316	8042	2.23	515,544	5980	1.66
Phu Yen	521,433	5423	1.51	347,622	4032	1.12
Thanh Hoa	510,188	5306	1.47	340,125	3945	1.10
Nhge An	455,134	4733	1.31	303,423	3520	0.98
Dak Lak	375,399	3904	1.08	250,266	2903	0.81

The Gai Lai province has the highest calculated energy potential from all the provinces (in total, almost 4 TWh per year). Its potential of sugarcane residues represents one-seventh of the country's full energy potential. It is also higher than the total potential of several entire regions (Northern midlands and Mountain areas, Mekong River Delta, Red River Delta) (see Tables 8 and 9). This potential corresponds to the energy consumption of over 860,000 households.

Moreover, as discussed above, to use biomass as biofuel more efficiently, pretreatment is important. Especially in the case of sugarcane residuals, drying and moisture reduction are essential for increasing the calorific value and thus obtaining higher energy yield. Using the example of the sugarcane bagasse, Figure 4 displays the significance of the difference between the energy potential of moist biomass (moisture content over 32%) and dry basis biomass, i.e., 15.55 TWh per year vs. 24.63 TWh per year for Vietnam, respectively.

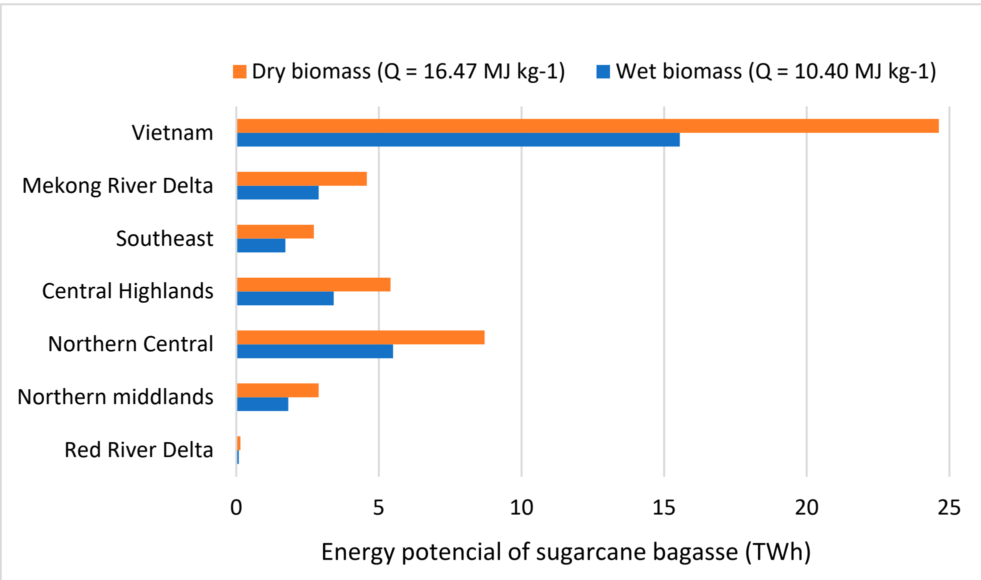

Figure 4. Impact of pretreatment on bagasse yearly energy potential.

4. Conclusions

The most important agricultural crops in Vietnam are paddy rice and sugarcane, with an annual production of more than 44 million tons and nearly 18 million tons, respectively. The production of these crops has been increasing in recent years, which was indisputably associated with the growing amounts of residues that are unused and contributes adversely to the environment and sustainable farming in general.

Rice residues, especially rice straw, offer an alternative material for energy use, which meets the requirements of minimizing CO_2 emissions, i.e., renewable energy source and fulfils the main preconditions, i.e., material in vast concentrations, readily available and on a dry basis. From the point of view of logistics and energy density improvement, the most appropriate option is the production of briquettes or pellets. The unfavorable property for pellets is the relatively high ash content (>10 wt.% dry in rice straw and >13 wt.% dry in husks); therefore, combustion in boilers with structurally adapted ash removal mechanisms is to be considered. Nevertheless, thanks to its composition, rice ash could be used for soil amendment. Similarly, rice husks are a suitable source of energy; furthermore, in a state that allows pressing into briquettes or pellets directly, i.e., without mechanical disintegration. On the other hand, husks may find another usage such as poultry litter. This implies a certain price of the material and economic calculations must be performed.

The energy use of sugarcane residues again meets the requirement of significant amounts in large concentrations in one place. Furthermore, also partly, relatively low moisture content; thus, it can be burned directly, which is typically done. However, for enhancing the energy potential and more efficient application and through briquetting or pelleting, it is necessary to dry the material up to 15% moisture. This biomass is also characterized by high ash content (nearly 12 wt.% dry for bagasse), so that solution could be the same as in the case of rice residues.

The present research revealed the potential and abundancy of leftover biomass and mapped in detail the situation throughout the whole country. It was calculated that the total annual energy yield of rice and sugarcane residues is about 443 TWh (416 TWh and 27 TWh accordingly), which is equal to the energy consumption of approximately 92 million average Vietnamese households in the form of electricity and energy for cooking per year. Finally, the maximization of energy production from biomass sources and the number of households or small local industries that will benefit from biomass-based energy is directly proportional to the selected pretreatment and technologies for biomass processing and/or biofuels production.

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