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Review

Availability and the Possibility of Employing Wastes and Biomass Materials Energy in Jordan

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Abstract: The state of Jordan's energy independence is critical, with the country relying almost entirely on imported oil and gas. Consequently, energy availability is considered to be the most significant challenge faced by Jordan's industrial sectors. Between 2014–2019, the Jordan generated over 12,000 kilo-tons of waste and residue each year. The available quantities of agricultural residues and animal wastes produced in Jordan were approximately 1284.2 kilo-tons/year and 10,909.6 kilotons/year, respectively, of which an estimated 42% could be used as a source of biogas. Two options for utilizing biomass resources have been reviewed in this paper: thermal treatment (direct combustion) and as a source of biogas. The quantity of biogas that can be produced in Jordan from a variety of biomass feedstocks is estimated to be 816.2 million cubic meters (MCM), which is equivalent to a yearly power output of 960.9 GWh, representing approximately 5.1% of the total electricity consumed by Jordan in 2019 (18,853 GWh). Assuming a thermal efficiency of 70%, biogas can generate as much as 4.8 TWh of heat energy. Alternatively, the direct combustion of various biomasses can provide Jordan with 2316.7 GWh of electricity. These findings may lead to the development of a long-term strategic plan for the intelligent utilization of available biomass feedstocks for electrical generation and/or as a source of biogas. This would consequently raise the proportion of sustainable energy derived from biomass in Jordan's energy mix. This work aims to assess the technical, economic, and environmental aspects associated with incorporating biomass resources into Jordan's energy network.

Keywords: biomass; biomass energy; biogas production; energy saving; emissions diminishing

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1. Introduction

The world's increasing reliance on energy has become a global issue [1–4]. However, conventional fuels used for energy generation, such as natural gas or diesel and coal, produce greenhouse gases (GHGs) [5–8] and contribute to climate change [9–11], most notably in carbon emissions [12], which increased by 2.7% in 2018 [13]. Consequently, most developed countries use reliable, clean, cheap, and safe energy sources instead of conventional fuels [14–16]. Natural waste (i.e., biomass) provides the best solution to obtaining these goals [17–19], as it can provide sufficient amounts of clean energy [9,20]. However, employing the use of biomass in Jordan could have a significant effect on net annual electricity generation. Doing so would reduce the use of fossil fuels, reduce CO_2 emissions, and have positive social impacts by potentially creating new jobs and increasing local wages.

Agricultural, municipal, and industrial sources generate millions of tons of solid waste worldwide [10]. These figures are expected to rise as the world's population grows and the extent of urbanization increases [21]. Biomass is abundant on Earth and is considered one of the most common sources of renewable energy (RE) [22]. Biomass is the world's fourth-largest source of energy, accounting for up to 35% of primary energy demand in some countries [23]. Jiang et al. [24] concluded that biomass accounts for 8.5% of total global energy usage, making it the fourth most crucial energy source worldwide [24]. Biomass is a sustainable carbonaceous material generated from the activities of biotic organisms (plants, algae, and animals). It can take the form of residues from trees, forests, and energy crops, from agricultural, animal, or human waste, as well as the organic fraction of municipal solid waste (MSW), waste from food manufacturing processes, and sewage sludge [25]. Biomass has a nearly 10–40% lower calorific value compared to petroleum-based fuel [26]. Biomass is nonhomogeneous, has a low grindability index, high moisture content, and a high O/C ratio [26]. Consequently, biomass represents a potential energy source that could reduce Jordan's reliance on crude oil [27]. The moisture content of animal waste is dependent on production conditions, as well as the manure-cleaning procedure. For example, the moisture content of poultry litter ranges from 7–49% [28], cow dung analysis revealed that it has an average moisture content of 41.2% [29], while the moisture content of MSW ranges from 55–65% [30]. Furthermore, the heating values of animal waste range from 12.3–16.9 MJ/kg dry waste, while the heating values for MSW are approximated to be 11.49 MJ/kg [31,32]. A variety of thermal, biological, and physical processes can be used to convert biomass into various types of biofuel or energy [27]. Justo et al. [33] investigated the availability and energy potential of herbaceous and vegetable residues generated by agricultural activity in Argentina. Their estimations yielded a residual biomass availability of 204.536 kilo-tons/year, suggesting an annual energy potential of 2605 TJ. This quantity of biomass, if used to produce electricity, can supply energy to up to 76,000 Mardel Plata city residents. In Bangladesh, the total amount of predicted biomass generated between 2012 and 2013 was 90,210 kilo-tons, corresponding to 321,240 kilo-tons of oil equivalent (Mtoe) or 373.71 TWh of electricity [34]. In 2011, the quantity of waste and residue was approximated to be 6680 kilo-tons. The quantity of biogas that can be generated from a variety of biomass sources in Jordan is approximated to be 428 MCM, equivalent to an annual power generation of 698.1 GWh. Based on 2011 data, this amounts to approximately 5.09% of total consumed electricity (13,535 GWh) and 39.65% of total imported electricity [25]. Jordan generates over 5.83 MT of waste and residue per year, approximately 42% of which can be obtained and used for energy and biogas production. The quantity and power potential of annually obtainable Jordanian biogas are approximately 313.14 MCM and 847.39 GWh, respectively. The biogas produced could replace nearly 23.64% of Jordan's primary energy consumption in 2012 (0.656 kilo-tons of natural gas equivalent) [26].

The use of biomass resources for power generation and/or biofuel generation is crucial from both an economic and environmental standpoint. Few investigations have been conducted to demonstrate the significance of Jordanian biomass/biogas production. According to Al-hamamre et al. [26], Jordan is theoretically able to generate roughly 706.9 MCM of biogas annually, even without considering energy availability; this is roughly the equivalent of 388.1 MCM of natural gas annually or 2.57 MCM of barrel oil annually. Al-hamamre et al. [25] also found that Jordan has the potential to generate approximately 428.19 MCM of biogas and approximately 235.5 MCM of methane (CH_4) annually. The average calorific value of Jordan's MSW was estimated to be 11.49 MJ/kg based on its physical composition and was related to the paper-to-plastic ratio of the waste [35].

The high cost of biodiesel is a major barrier to its commercialization. The manufacturing process is heavily influenced by the capacity of the plant, process technology, chemical expenses, and the price of raw materials. In most cases, the production costs associated with small- or moderately sized plants make biofuels considerably more costly than diesel [36].

Bioethanol is generated from lignocellulosic biomass, as well as sugar/starch-containing crops. However, the cost of producing bioethanol from lignocellulose is still prohibitively high [37]. Furthermore, commercial large-scale technology for producing bioethanol from lignocellulose has yet to be fully developed [38]. The technology required to produce sugar/starch crops is also relatively immature and costly [39].

Jordan is a Middle Eastern country surrounded by countries with a history of conflict, such as Iraq, Palestine, and Syria. Consequently, Jordan is under a significant degree of pressure to satisfy the needs of both its citizens and refugees [40]. In addition, 80% of Jordan's land area (90,000 km^2) is a highly arid desert [41] that is difficult to survive in [42]. Consequently, Jordan's local energy resources, such as water, energy, and agriculture, are limited [43]; local resources only account for 2.4% of Jordan's total energy consumption [26]. Jordan is thus heavily reliant on imported food. Jordan's population increased from 6 million in 2011 to 10.5 million in 2019 [40], and is expected to grow from 9.4 million in 2015 to 12.8 million in 2040 [44].

Despite Jordan's ability to use biomass-derived energy resources, there has been little research into biofuels and their applications. Al-hamamre et al. [25] investigated Jordan's biomass production and its potential as a power source, including MSW, agricultural residues, and animal wastes. Al-hamamre et al. [26] characterized Jordan's diverse biomass resources and suggested initiatives to use such biomass feedstocks in renewable energy projects. However, Jordan has shown little to no interest in its biomass resources, and more research is needed to estimate its annual biomass availability.

This work aims to (i) determine the state of biomass production in Jordan; (ii) assess the availability of Jordan's biomass residues for agro-energy purposes, specifically heating, biogas yields, and power generation; (iii) to promote and inspire both the private and public sectors to take part in the management and growth of the biomass power sector; and (iv) to find more effective and environmentally friendly uses for biomass, MSW, and other organic wastes while minimizing their effects on ecosystems.

Here, we review the range, scope, and comprehensiveness of the literature on biomass and the potential of Jordanian biofuel production.

2. Electricity Generation in Jordan

Similarly to many other nations, Jordan faces significant issues in meeting national energy demand on a consistent and secure basis due to its limited supplies of locally accessible carbon fuels, an inadequate number of accessible conversion facilities, and the financial vulnerability of its energy corporations [45]. This section reviews the consumption and price of Jordanian electricity.

Electricity Consumption in Jordan

Important indicators for the Jordanian electricity sector are reported in Table 1, which collected and calculated depend on the ref. [46]. The projected energy demand in Jordan is collected and presented in Table 2 [47]. In 2017, Jordan had an installed energy capacity of 4.5 GW with a peak load of 3.4 GW, and a power generation capacity of approximately 20.8 TWh. Energy demand in Jordan from 2008 to 2020 is collected and shown in Figure 1 [46]. Over the last two decades, policymakers have attempted to rely primarily on natural gas as a source of electricity due to its greater economic viability compared to other options. Figure 2 illustrates the proportion of fuels used for electricity production in Jordan between 2015 and 2017, which are collected and presented. Jordanian electricity demand is expected to increase from 19.0 TWh in 2015 to 82.4 TWh in 2050, as shown in Figure 3 [46,48]. Albatayneh et al. [49] estimated the peak load on the electrical system in Jordan to be 3205 MW and 3380 MW in January 2018 and January 2019, respectively, indicating a growth rate of approximately 5.5%. This is in contrast to the annual growth of Jordan's electricity generation capabilities between 2010 and 2019, which was estimated to be 2.7% [49]. Thus, Jordan faces considerable challenges associated with the growth of its peak electrical load, which grows by 3–5% per year, necessitating an adaptation of Jordan's energy system [49].

Table 1. Indicators for the electricity sector in Jordan.

Description	Type	Unit	Year				Average Yearly Growth Rate
			2017	**2018**	**2019**	**2020**	**(%/Year)**
Peak Load (MW)		MW	3205	3320	3380	3630	4.4
Available Capacity (MW)		MW	4300	5236	5255	5424	8.5
Generated Energy (GWh)	-	GWh	19,287	18,913	19,273	19,194	1.4
Consumed Energy (GWh)	-	GWh	18,963	18,539	18,853	18,863	1.4
Imported Energy (GWh)	-	GWh	51	188	239	381	118.4
Fuel Consumption for Electricity (Thousand tons of oil equivalent, T.T.O.E)	-	-	3804	3526	3361	3202	5.9

Table 2. Energy demand projections through 2030 in Jordan [47].

Year	Energy Demands (Max.)		Electrical Energy Produced	
	(MW)	Growth Rate (%)	(TWh)	Growth Rate (%)
2014	2915	10.0	18.2	5.1
2015	3096	6.2	19.1	5.1
2016	3281	6.0	20.2	5.4
2017	3482	6.1	21.3	5.7
2018	3704	6.4	22.6	6.0
2020	4198	6.5	25.6	6.4
2030	8014	6.7	48.3	-

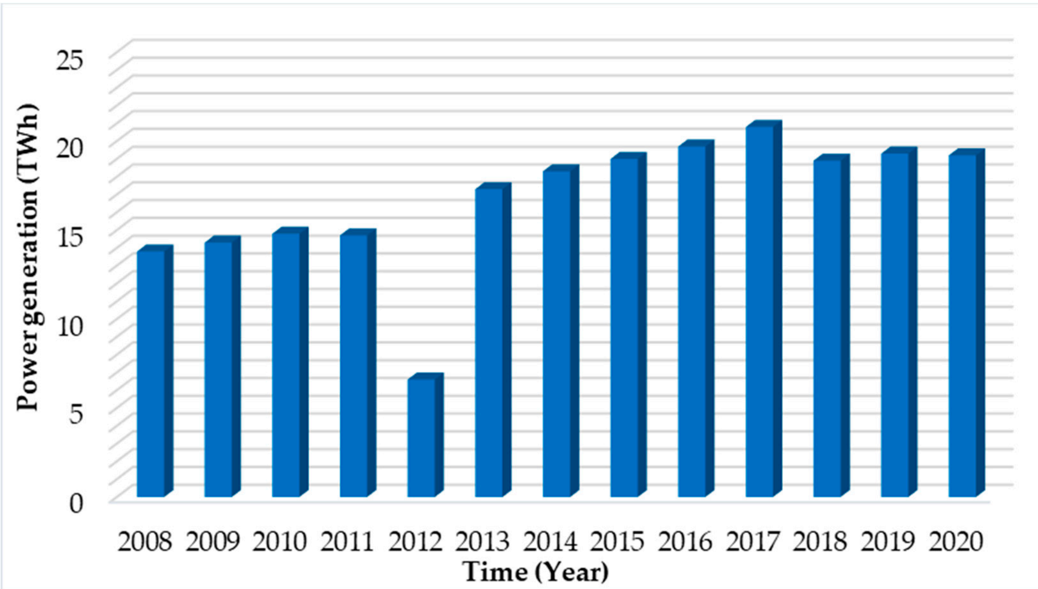

Figure 1. Jordan's energy demands growth over the last decade.

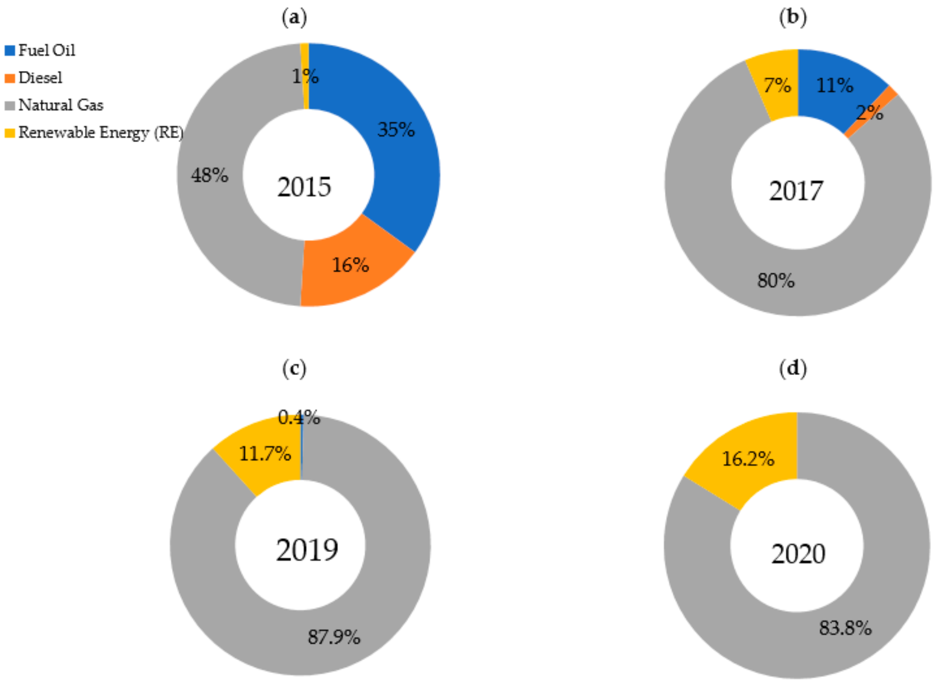

Figure 2. Electricity production mix throughout (**a**) 2015, (**b**) 2017, (**c**) 2019, and (**d**) 2020.

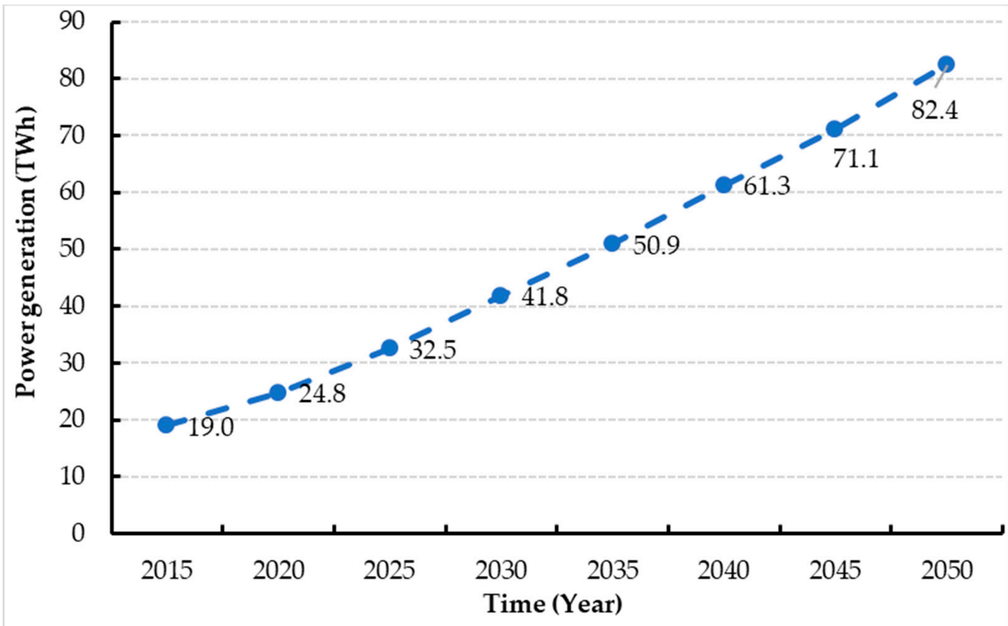

Figure 3. Jordan's electricity demands throughout 2015 and 2050.

3. Energy in Jordan

Across all sectors, energy is regarded as one of the most difficult challenges facing Jordan. Energy is expensive and hinders industrial development. The use of renewable energy resources, such as biomass, can provide significant environmental benefits, such as reducing GHG emissions and environmental pollution, while also eliminating local organic wastes (animals and vegetables).

3.1. Non-Renewable Energy in Jordan

Jordan's energy situation is dire [50], and the country is almost entirely reliant on imported oil and gas [49,51]. Jordan has major problems with energy dependence and the high cost of energy across all sectors [47,50,52]. In particular, it faces great difficulties in ensuring that it can maintain a stable and secure power supply system for the industrial sector's growing energy needs [53]. Jordan's energy needs were approximated to be 7.58 Mtoe in 2007 and are projected to increase to 15.08 Mtoe by 2020 [54]. Abu-Rumman et al. [55] found that approximately 94% of Jordan's fossil fuels (oil and gas) were imported to meet energy demands.

3.2. Renewable Energy in Jordan

Jordan is presently dealing with several environmental and energy-related concerns [56,57]. Adopting RE resources could improve Jordan's energy security, providing significant socioeconomic advantages to Jordanians [58,59]. Doing so would also provide several environmental benefits by reducing GHGs and CO_2 emissions [60–62], and mitigating climate change [63–65]. Jordan's Renewable Energy and Energy Efficiency Law (JREEEL) was passed in 2010 [66]: this strategic policy set the goal of increasing the contribution of sustainable energy to Jordan's energy budget from 2% in 2011 [26] to 10% by 2020 [67], with wind, solar, and biomass expected to provide 600–1000 MW, 300–600 MW, and 30–50 MW of energy, respectively [51]. Due to these investments, Jordan is ranked first in the MENA region in terms of the attractiveness of its RE sector [68]. However, Hamed and Bressler [58] reported that only 4% of Jordan's energy was derived from renewable sources in 2019 [58] and expected to reach 11% [47,69]. During the last Egyptian gas outage, Jordan's National Electric Power Company (NEPCO) lost USD 6 billion [70]. Similarly to other developing nations, Jordan faces several energy concerns, limitations, and obstacles that necessitate the increased utilization of RE technology [71]. Its national targets may not be met unless the necessary assistance for the RE sector is provided [67].

4. Methodology

This section reviews the range, scope, and comprehensiveness of the literature on the applications of biomass for the production of biogas, as well as for thermal energy generation through direct combustion in Jordan. An accurate biomass assessment is critical in determining the potential and impact of bioenergy, especially concerning the production and utilization of such resources. The estimates presented in this study consider the local accessibility and supply of biomass in various geographical locations throughout Jordan, including:

1. Assessing the quantity of biomass generated in Jordan, as well as defining the type and diversity of crops planted and their harvests. A six-year average (2014–2019) was used as the study period.
2. The quantity of Jordan's dry biomass residues was approximated based on the amount of biomass produced by a variety of sources. In particular, the quantity of animal manure was dependent on the livestock population.
3. The factors for accessibility and potential energy for agricultural, MSW, and livestock residues were set at 0.25, 0.75, and 0.125, respectively, to determine the potential power generation that could be obtained from these residues.
4. The volume of biogas and the amount of energy that could be generated from various biomass resources in Jordan were approximated using data from similar field research.
5. The availability and the applicability of adopting biomass as an energy resource in Jordan were investigated from several socioeconomic and environmental perspectives.

5. Biomass Resources in Jordan

Jordan generates large amounts of animal, human, and agricultural waste each year, of which one-third is food waste [21]. Mousa [40] reported that approximately 50–65% of global food is disposed of as waste, which is significantly higher than Jordan's food wastage. In Jordan's local communities, bread is the only food waste that is recollected and reused as animal food. During Ramadan, about 0.600 kilo-tons of food are lost; during this time, there is a noticeable increase in food disposal compared with other months of the year [40]. The primary sources of organic waste in Jordan are MSW, animal waste, and olive waste [27]. Food and paper waste account for the majority of solid waste generated in the major three cities (Amman, Zarqa, and Irbid) [26]. Al-Hamamre et al. [26] found that the average organic fractions of food and paper waste were approximately 68.3% and 12.6%, respectively. Plastic is the third most common solid waste and has an average organic fraction of 8.6%. Combustible waste includes wasted food, paper, cardboard, and plastic; it accounts for nearly 90% of Jordan's total waste. The non-combustible waste fraction includes metal ceramics and glass, and clay, which account on average 2.5% and 6.1% of MSW, respectively. Unfortunately, despite its good energy value, there are no industries that can utilize biomass resources in Jordan, with the exception of a small amount of biomass utilized for space heating using direct combustion processes. Biomass projects should not have any negative impact on food security, should meet social requirements, and be cost-effective. Most of Jordan's biomass resources are dispersed throughout the country, and there is limited collection coverage. During biomass collection in Jordan, a significant amount of agricultural residue is lost, either by being burned or reused as animal food [26].

5.1. Solid Waste in the Southern Cities of Jordan

In addition to 0.040 kilo-tons of natural wood, about 0.100 kilo-tons of straw and sawdust are produced each year in the southern cities of Jordan, which include Karak, Ma'an, Tafilah, and Aqaba. While these quantities are significant, they do not pose problems for the region, as these materials can be used as animal food (straw) and/or heating sources (wood and sawdust). The optimal C/N ratio for conventional treatment methods, such as anaerobic digestion, is approximately 20–30 according to the literature. At low C/N ratios, ammonium (NH_4) is produced during the biodegradation process [21]. Al Momani et al. [21] conclude that the experimental chemical analysis of these solids shows that the C/N ratio of straw, sawdust, wood, and cattle produced in this region is approximately 34, 33.5, 33, and 24, respectively. Furthermore, the chemical oxygen demand (COD) of straw, sawdust, wood, and cattle was found to be almost 450, 380, 380, and 240, respectively, while the biological oxygen demand (BOD) of straw, sawdust, wood, and cattle was approximately 435, 366, 370, and 189 (mg/L), respectively. The biodegradability index of straw, sawdust, wood, and cattle was found to be 0.97, 0.96, 0.97, and 0.79 (mg/L), respectively [21].

5.1.1. Animal Manure

In 2005, there were more than 2.4 million sheep, 72,000 cows, and 40 million chickens spread across Jordan's governorates [27], while approximately 62.59 million animal heads were reported in Jordan in 2019 [72]. In 2013, Al-Hamamre et al. [26] conducted a survey that investigated the national distribution of animal farms (including goats, sheep, and cattle). They found that northern governorates possessed the highest concentration of animal farms at 36.5%, followed by middle and southern governorates at 34.1% and 29.4%, respectively. The total animal waste from these farms was found to be 2114.09 kilotons/year [26]. Between 2014–2019, the total obtainable amount of livestock manure was estimated to be 10,909.6 kilo-tons. Goats and sheep contribute the most to the amount of animal manure at 26.4%, as illustrated in Table 3, these date are calculated and analyzed depend on the data collected from various references. However, in some local villages, animal manure is used as soil fertilizer by disposing of them in open and uncovered areas, where it is washed into the soil by rain [26]. However, this application of animal manure can potentially cause environmental issues such as surface and groundwater pollution [73]. Abu-Ashour et al. [27] showed that the overall BOD content of Jordan's animal waste was 200 kilo-tons per year, while Al-Hamamre et al. [26] showed that the animal manure had calorific values ranging between 13.50–17.80 MJ/kg. The quantity of animal manure that could be converted into energy was found to be 1255.5 kilo-tons, which possesses an energy content of nearly 18.45 PJ (18.45×10^{15} J) [26], especially since poultry has a high energy content (54.6%). In contrast, sheep and goats have a proportional energy content of 25.9%, while cattle, camels, and horses and donkeys have proportional energy contents of 18.73%, 0.47%, and 0.33%, respectively [26].

5.1.2. Municipal Solid Waste (MSW)

MSW refers to waste produced by households, businesses, and industries, and includes plastic, glass, textiles, metal, and biodegradable materials such as paper [26]. Solid waste management is considered to be a complicated procedure, especially in developing nations [77,78]. MSW is a crucial component of GHG reduction action plans and strategies worldwide [78] and accounts for nearly 10% of overall emissions in Jordan [44]. Approximately 1960 kilo-tons of MSW were reported in 2011 [25], and approximately 2700 kilo-tons were reported in 2014. The growth rate of MSW has been estimated at 3% per year [26]. Consequently, Jordan was expected to generate 2500 kilo-tons of MSW by 2015 [25]. However, the actual amount of MSW produced in 2015 was 3460 kilo-tons [44]. Hatamleh et al. [79] reported that, in 2020, Jordan generates 2077.215 kilo-tons of MSW/year, with a per capita waste creation rate of 0.9 kg/day in metropolitan areas. Al-Hamamre et al. [26] found that, in 2012, Jordan's MSW was comprised of 50% organic material, 16% plastic, 15% cardboard and paper, and 19% miscellaneous types. The estimated waste generation for rural areas and urban zones was reported as 0.6 and 0.9 kg per day per capita, respectively [26]. Al-Hamamre et al. [26] concluded that the MSW has an energy content of about 11.49 MJ/kg. In Jordan, MSW is disposed of in landfills, the largest of which, Al-Ghabawi, is located in Amman. Approximately 84% of the waste disposed of in this landfill is total solid (TS) waste, representing 58% of Jordan's total TS waste by volume [26]. Nearly half of Jordan's MSW is disposed of in this landfill [44], followed by the Akeedar landfill, which is located next to the Mafraq governorate's main road. Akeedar is Jordan's second-largest landfill, with an area of 0.806 km^2. In total, 45% of the waste processed at Akeedar is TS waste, representing 9.2% of national TS waste by volume. Only 20% of the solid waste in Irbid city is transferred to landfills [26]. Fast-growing cities, such as Irbid, face significant challenges in collecting and handling solid waste. This is due to significant changes in the city's demographics, especially since Irbid hosts many Syrian refugees [79]. In Aqaba, a 120,000 m^2 landfill can be found around 17–20 km from the city center. It receives almost 0.080–0.120 kilo-tons of MSW per day, with trenching being the primary method of dealing with the waste disposed of in this landfill. This method entails depositing solid waste in an excavated area without a bottom liner. When the excavated area has been depleted, the solid waste is covered by soil. Figure 4 shows a 20-year projection of the generation of MSW (2010–2030) [26]. Abu Hajar et al. [44] concluded that, if the MSW management industry continues to develop at its current rate, net GHG emissions will climb to 5698 Gg CO_2-eq by 2025, accounting for 14.5% of GHG emissions in Jordan. The Jordan 2025 vision set a goal of reducing solid waste disposed of in landfills or dumpsites by 33%, replacing this method of waste disposal by anaerobic digestion, composting, and incineration [44]. This would allow the organic material of MSW to be transformed into electricity and heat or a more adaptable power source such as gaseous or liquid fuels via thermochemical and biochemical processing methods. Waste-to-energy (WtE) projects operate by incinerating waste; the heat obtained is transformed into energy. Consequently, most projects continue to utilize this technology even in the present day [26]. Jordan has twenty-three wastewater treatment plants [25] that have a total daily average flow rate of approximately 216,412 m^3/d. This number is expected to grow to 237 MCM/year by 2020. Annually, treatment plants produce 2 MCM of sewage sludge; this massive amount of sewage sludge can be used to generate biogas [25].

Table 3. Number of livestock, approximated generation of waste, and energy output for the years 2014–2019 [72,74–76].

Livestock													
Type	**Year/Thousand Head**						**Average Heads Number**	**Annual Dry Wastes Ratio**	**Dry Waste Yield**	**Calorific Value**	**Energy Content of Waste**	**Availability Factor of Energy**	**Potential Energy of Wastes**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**							
	(10^3 Heads)	**(10^3 Heads)**	**(10^3 Heads)**	**(10^3 Heads)**	**(10^3 Heads)**	**(10^3 Heads)**	**(kton)**	**(ton/Head/Year)**	**(kton/Year)**	**(MJ/kg)**	**(TJ)**	**(-)**	**(TJ)**
Sheep	2680.3	3170.0	3279.1	3833.3	3458.8	3107.2	3254.8	0.7	2278.0	17.8	40,548.9	0.125	5068.6
Goat	857.0	1007.0	1098.0	1146.0	1035.0	0.9	857.3	0.7	600.0	17.8	10,680.6	0.125	1335.1
Cattle	857.0	1007.0	1098.0	1146.0	4494.0	3018.1	1936.7	3.6	6972.0	15.0	104,580.6	0.90	94,122.5
Camel	13.0	13.0	11.0	11.0	10.9	10.9	11.6	3.6	41.8	14.9	623.5	0.125	77.9
Poultry	45,368.0	42,517.4	42,521.4	44,244.4	46,431.8	56,453.9	46,256.2	0.022	1017.6	13.5	13,738.1	0.90	12,364.3
Total	49,775.3	47,714.4	48,007.5	50,380.7	55,430.5	62,590.9	52,316.6	-	10,909.6	-	170,171.6	-	112,968.4

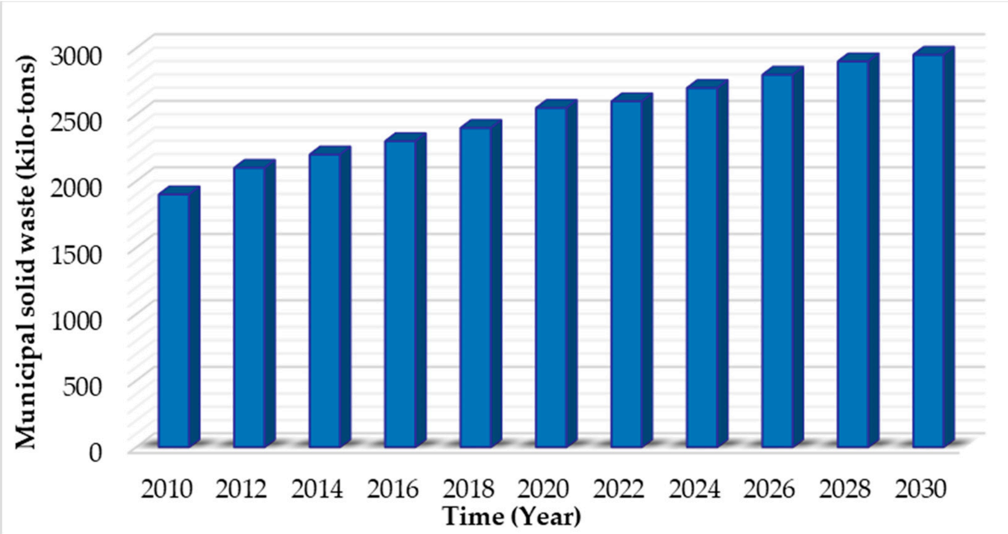

Figure 4. The projected amount of municipal solid waste in 20 years (2010–2030) [26].

5.2. Agricultural Residues in Jordan

Even if water is available, most of Jordan's soil is unsuitable for agriculture. Only 6% of Jordan's territory is arable. In recent years, only 15% of Jordan's geographical area received more than 200 mm of total annual rainfall, which is the bare minimum needed for rain-fed farming. Only 4.5% of Jordan's land is currently being cultivated, and a majority of these cultivated areas are heavily reliant on irrigation. The total quantity of energy crops that could have been grown on 10%, 20%, and 30% of arable land in the southern cities of Jordan was calculated. It was found that it was possible to cultivate 30,000 km^2 of energy crop farms using 10% of the arable land in southern cities. This amount of energy crop production is capable of meeting the region's energy demands [21].

5.2.1. Vegetable Residue

In Jordan, vegetables are the primary crop cultivated on irrigated land. Most of Jordan's vegetable production is located in the Jordan valley (irrigable lands), as well as some areas in northern and central Jordan that experience high annual rainfall of 400–600 mm per year [26]. Al Momani et al. [21] estimated the proportion of agricultural land in Jordan to be only 11.29% in 2011. Furthermore, 9.61% of the total agricultural land area required irrigation, which necessitates a controlled flooding system. Al-Hamamre et al. [25] found that Jordan produced approximately 997.25 kilo-tons of vegetable residues in 2011, representing an energy content of 7.954 PJ (in dry base); this would have accounted for 2.48% of Jordan's total primary energy consumption in 2011. Thus, these residues would have made a significant contribution to Jordan's energy sector [25]. Between 2014–2019, the average annual tomato dry waste was 106.8 kilo-tons. Tomato dry waste was found to have a moisture content of 80–90%, a calorific value of 6 MJ/kg, and the potential energy in the residue was calculated to be 160.2 TJ using an energy availability factor of 0.25. Similarly, the average annual potato dry waste was found to be 0.0488 kilo-tons with a moisture content of 55–65%, a calorific value of 6 MJ/kg, and the potential energy within the residue was found to be 73.1 TJ at an energy availability factor of 0.25 (Table 4). These data are collected from different research papers and reports, presented, and calculated the data of vegetables biomass. Note that the quantity of residue was approximated using the available and previously reported ratios [72,76,80,81]. Tomatoes occupy the greatest proportion of vegetable waste products in Jordan [25]. About 33–40% of fresh tomatoes eventually end up as bio-waste [82]. The majority of this waste is in the form of tomato skins and seeds [83] generated through the industrial process of tomato ketchup, salsa, and paste [83–85]. It is thus possible to obtain alkyd resins and biofuels from tomato residues [82]. The energy content in residues is similar for most vegetable products (approximately 6 MJ/kg). Jordan considers vegetable residues to have a low energy availability factor of 0.25. Most vegetable waste is lost or burnt at farms due to collection difficulties, and a substantial portion of it is used as fertilizer and animal feed [25].

5.2.2. Fruit Residues

In total, 917.9 kilo-tons of fruit were produced in Jordan in 2019. The olive is the most important fruit in Jordan and is cultivated over an area of 107 kilo-hectares [26]. Olive groves account for roughly 73% of Jordan's overall tree-planted agricultural area [86]. These figures show that olive oil production is one of the country's most crucial agri-business sectors. Half of Jordan's olive trees are grown in northern Jordan [86], which has irrigated lands, while the other half is grown in the western mountains, with rain-fed lands. There are an estimated 17 million olive trees in Jordan, with a growth rate of about 1 million trees per year [26]. Al-Hamamre et al. [25] found that the quantity of dehydrated olive cake made as a byproduct in olive extraction plants can be estimated, assuming that olive cake accounts for 35–45% of the mass of an olive fruit and that 60–70% of this amount can be acquired as dry olive cake. Based on these assumptions, 100 kg of olive fruit can generate about 26 kg of dry olive cake [25]. Abu-Ashour et al. [27] found that around 27.0 kilo-tons of olive waste were generated in 2005, with a waste collection efficiency of 70%. The overall heating value of these wastes was calculated to be 6600 million MJ or 157 ktoe. This amount would account for 84% of Jordan's domestic crude oil and natural gas output [27]. Al-Hamamre et al. [26] reported that Jordan produced 34.268 kilo-tons of olive cake in 2011. The measured calorific value and ash content of this residue was found to be 24.5 MJ/kg and less than 3.27%, respectively. In 2010 and 2011, the average price of olive cake would have been around USD 84.5 per ton, i.e., the 34.268 kilo-tons of olive cake produced in Jordan would have been worth USD 2.9 million and represented a total energy of approximately 0.84 PJ. The second most commonly produced group of fruits in Jordan are citrus fruits (e.g., grapefruit, lemon, and orange), cultivated over 6.882 hectares, accounting for 25.3% of total Jordanian fruit production. Citrus fruit farms are mainly located in northern Ghour and central Jordan (irrigated lands) [26]. Between 2014–2019, the average annual mass of residue generated by citrus fruits and olives was reported to be 207.4 kilo-tons and 344.9 kilo-tons, respectively. These residues had calorific values of 13.0 MJ/kg and 15.2 MJ/kg, respectively, and the potential energy of these residues was calculated to be as 674.1 and 3931.9 TJ using energy availability factors of 0.25 and 0.75, respectively. Overall, the total amount of fruit residue produced was estimated to be 940.3 kilo-tons/year with a total energy content of 13,439.3 TJ. Using the average energy availability factor of most fruit residues (0.25), the total potential energy that can be derived from fruit residue was estimated to be 5981.1 TJ, with olive and citrus fruit residues accounting for 65.7% and 11.3% of total potential energy, as illustrated in Table 5. Table 5 presented the vegetable biomass in Jordan, which are collected from different research references and reports that help in calculation and presented the residual data.

Table 4. The significant vegetables grown in Jordan between 2014 and 2019, the approximate average residues generated, and their energy possibilities [72,76,80,81].

Vegetables												
Type	**Yearly Production (Kilo-Ton)**						**Average Yearly Cultivation**	**Moisture**	**Dry Waste Yield**	**Calorific Value**	**Potential Energy of Residues**	**Availability Factor of Energy**	**Potential Energy of Residues**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**							
	(kton)	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(%)**	**(kton)**	**(MJ/kg)**	**(TJ)**	**(-)**	**(TJ)**
Tomatoes	727.9	892.0	774.9	643.7	750.6	483.7	712.1	80–90	106.8	6	640.9	0.25	160.2
Potato	127.5	126.8	120.0	74.0	272.7	182.0	150.5	55–65	48.8	6	292.5	0.25	73.1
Eggplants	124.1	141.0	136.1	132.6	60.5	52.8	107.9	80–90	8.1	6	48.5	0.25	12.1
Cucumber	164.4	291.1	293.6	217.5	286.5	209.7	243.8	80–90	18.3	6	109.7	0.25	27.4
Watermelon	92.8	90.1	47.8	30.2	49.9	75.8	64.5	80–90	4.8	6	29.0	0.25	7.3
Melon	57.6	54.5	23.9	24.4	25.8	38.5	37.4	80–90	2.8	6	16.8	0.25	4.2
Others	358.7	57.6	256.6	530.6	1131.6	631.9	494.5	80–90	37.1	6	222.5	0.25	55.6
Total	1653.0	1653.0	1653.0	1653.0	2577.5	1674.4	1810.6	-	226.7	-	1360.1	-	340.0

Table 5. The major fruits grown in Jordan between 2014 and 2019, the approximate average residues generated, and their energy possibilities [72,76,80,87,88].

Fruits												
Type	**Yearly Production (Kilo-Ton)**						**Average Yearly Cultivation**	**Moisture**	**Dry Waste Yield**	**Calorific Value**	**Potential Energy of Residues**	**Availability Factor of Energy**	**Potential Energy of Residues**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**							
	(kton)	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(%)**	**(kton)**	**(MJ/kg)**	**(TJ)**	**(-)**	**(TJ)**
Olive	128.2	263.3	263.3	245.4	212.5	365.5	246.4	-	344.9	15.2	5242.5	0.75	3931.9
Citrus	161.0	161.0	161.0	245.5	131.7	176.9	172.8	35–45	207.4	13.0	2696.4	0.25	674.1
Apricot	16.8	28.8	28.8	29.5	26.5	16.8	24.5	35–46	29.4	13.0	382.8	0.25	95.7
Grapes	47.1	138.6	138.6	13.2	58.8	47.1	73.9	35–47	88.7	13.75	1219.8	0.25	304.9
Banana	62.2	32.2	73.1	45.0	56.7	62.2	55.2	35–48	66.3	13.0–17.4	861.6	0.25	215.4
Apple	7.3	18.1	18.1	14.4	39.6	7.3	17.5	35–49	26.2	13.0	340.8	0.25	85.2
Others	492.3	273.0	232.0	165.3	131.4	479.3	295.5	35–50	177.3	13	2695.4	0.25	673.8
Total	915.0	915.0	915.0	758.3	657.2	917.9	846.4	-	940.3	-	13,439.3	-	5981.1

5.2.3. Field Crop Residues

Wheat is the primary rain-fed field crop cultivated by local farmers and Bedouins in areas with <350 mm of rainfall. According to the records collected by the Jordanian commerce ministry, Jordan imports more than 96% of its wheat requirements, with domestic production barely meeting around 4% of the nation's needs [89]. Between 2014–2019, the average annual dry waste generation of wheat, barley, and maize was reported to be 52.1 kilo-tons, 41.8 kilo-tons, and 10 kilo-tons, respectively, with a moisture content of 10–20% for wheat and barley and 11–22% for maize. The calorific values of wheat, barley, and maize were found to be 17.39 MJ/kg, 18.60 MJ/kg, and 17.39 MJ/kg, respectively, and the total potential energy from these residues were found to be 226.6 TJ, 194.3 TJ, and 43.6 TJ, respectively, based on an energy availability factor of 0.25, as illustrated in Table 6, which collected from different references and calculated based on that. It should be noted that the residues from these crops (such as leaves, husks, and straw stalks) are mainly reported at harvest time [26]. Al-Hamamre et al. [26] concluded that nearly 117.2 kilo-tons of agricultural residues are available for use in Jordan, representing resources with an energy content ranging from 14.65–18.60 MJ/kg. The total energy content of crop residues in Jordan is estimated to be 519.8 TJ [26]. Al Momani et al. [21] found that utilizing 10% of arable land in southern cities of Jordan for the cultivation of energy crops with a yield of 3, 5, and 10 tons of TS waste can provide 2.2 Mtoe, 4.6 Mtoe, and 9.0 Mtoe, respectively. Furthermore, utilizing 30% of arable land for the cultivation of energy crops with a yield of 3, 5, and 10 tons of TS waste can provide 7.3 Mtoe, 13.2 Mtoe, and 28.0 Mtoe, respectively, assuming a biomass conversion efficiency of 100%. However, it should be noted that these values must be recalculated after the initial phase of any biogas projects, as not all biomasses can be converted to biogas (the biomass conversion efficiency generally does not exceed 80%). These low quantities of obtainable energy may have a significant effect on Jordan's ability to supply crude oil and natural gas [21].

5.3. Electricity Generation from Biomass

The use of biomass for electricity production is becoming increasingly popular, and biomass is a readily available source of energy in rural areas. Furthermore, it is less harmful to the environment than energy derived from fossil fuels. It is thus considered to be an excellent source of electrical power and can be harnessed by the direct combustion of residues and/or the anaerobic digestion of animal manure [90]. In direct combustion methods, biomass feedstocks are fired with available air/oxygen to generate heat. This heat can be used to generate steam in a boiler, which is subsequently used to power a steam turbine attached to a generator to produce electricity. Figure 5 depicts a typical setup for biomass energy production [26]. Al-Hamamre et al. [25] found that the cumulative theoretically available thermal energy that can be obtained from Jordan's biomass resources, assuming a conversion rate of 0.7, was 32.63 PJ, which is equivalent to nearly 20.1% of the total electricity consumption in Jordan in 2011 (nearly 10.2% of the nation's primary power consumption). Taking an appropriate energy availability factor into account, the expected power that can be generated by biomass was 1210.5 GWh or 8.95% of total electricity usage in 2011, and the proportion of MSW within that energy is 7.3% [25]. Sagani et al. [91] found that this would result in a net positive annual electricity generation. The utilization of biomass would also reduce the need for fossil fuels, reduce CO_2 emissions, and have a positive social impact by creating new jobs for locals and increasing their potential earnings. In addition, the internal rate of return (IRR) of this venture was found to be relatively high [26]. Al-Hamamre et al. [26] concluded that the direct combustion of different biomass resources could provide Jordan with 2316.7 GWh of electricity, with relative contributions of 46.48%, 40.13%, and 13.39% for animal waste, MSW, and agricultural residue, respectively (Figure 6).

Table 6. The major farming crops grown in Jordan between 2014 and 2019, the approximate average residues generated, and their energy possibilities [72,76,80,88].

Farming Crops														
Type	**Yearly Production (Kilo-Ton)**						**Average Yearly Cultivation**	**Moisture**	**Dry Waste Yield**	**Calorific Value**	**Potential Energy of Residues**	**Availability Factor of Energy**	**Potential Energy of Residues**
	2014	**2015**	**2016**	**2017**	**2018**	**2019**							
	(kton)	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(kton)**	**(%)**	**(kton)**	**(MJ/kg)**	**(TJ)**	**(-)**	**(TJ)**
Wheat	25.1	30.6	34.4	53.7	29.9	31.9	34.3	(10–20)	52.1	17.39	906.6	0.25	226.6
Barely	28.4	41.6	39.5	27.2	38.8	51.3	37.8	(10–20)	41.8	18.60	777.1	0.25	194.3
Maize	6.5	6.5	6.4	6.5	0.3	5.1	5.2	(11–22)	10.0	17.39	174.5	0.25	43.6
Chickpeas	2.1	2.1	0.7	0.7	3.3	3.4	2.1	(10–20)	2.4	17.25	42.1	0.25	10.5
Lentils	2.2	2.6	2.0	2.4	0.6	0.3	1.7	(10–20)	2.7	14.65	39.5	0.25	9.9
Others	20.5	1.4	1.8	3.2	2.9	1.5	5.2	(10–20)	8.1	17.25	139.4	0.25	34.8
Total	84.9	84.9	84.9	94.0	75.2	93.6	86.2	-	117.2	-	2079.2	-	519.8

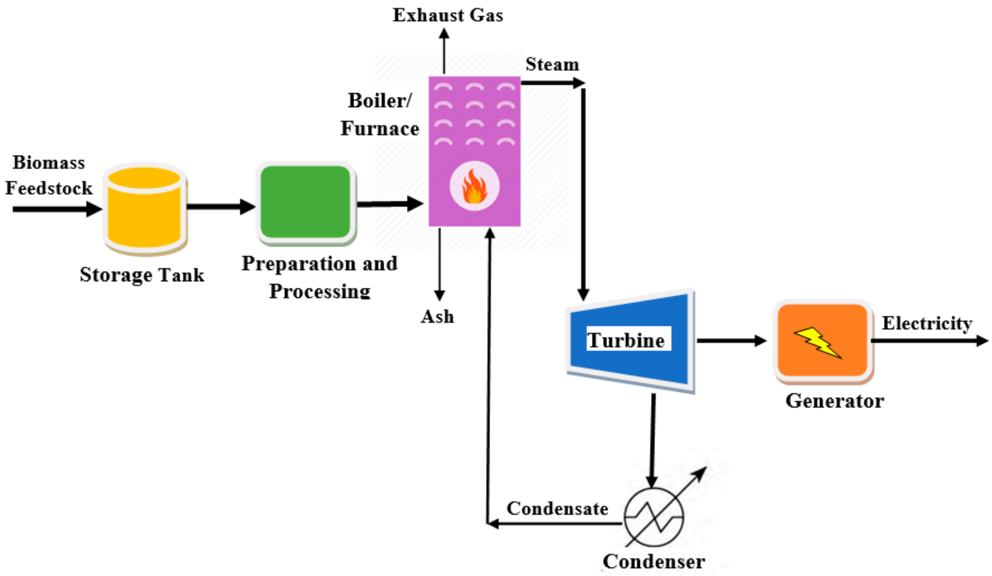

Figure 5. The layout of a biomass electricity generating system (direct combustion/steam turbine).

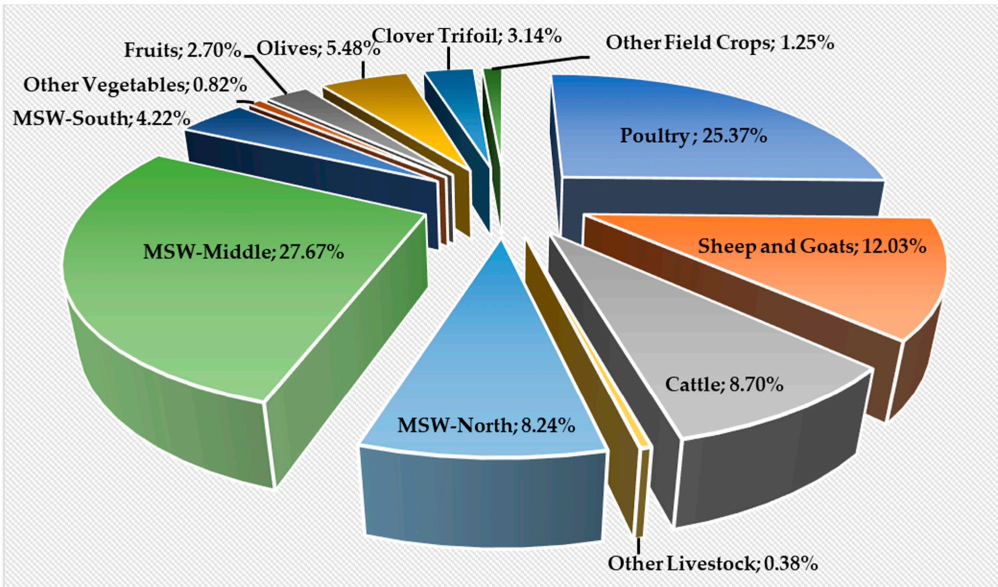

Figure 6. The contribution of significant biomass resources to energy production via direct biomass combustion in Jordan.

6. Biomass Technologies

6.1. Biogas Technologies

Biogas is a type of renewable or waste fuel produced by the fermentation of organic compounds [92] that can be adopted at the residential and commercial scale [93]. There are a variety of biomass resources that can be used to generate biogas, such as plants, waste from the agricultural industry, animal manure, and the organic fraction of MSW. Biogas is generally produced using an anaerobic digestion process, in which the biomass is sealed inside a heated anaerobic digester tank that provides a suitable environment for the growth of anaerobic bacteria/microorganisms [43]. In the absence of oxygen, these anaerobic bacteria can convert the available biodegradable compounds in organic wastes into biogas [92]. Al-Hamamre et al. [26] found that the percentage of biogas production from animal manure (sheep, goat, and cattle) compared to the total potential biogas production in the central, northern, and southern areas of Jordan was as high as 24.39%, 23.30%, and 18.74%, respectively. Milbrandt and Overend [94] found that fruit residues had the second-highest contribution to potential biogas production in Jordan (24.14%), with residues from olives, citrus fruits, bananas, and other fruits contributing 37.0%, 24.22%, 15.34%, and 23.45% to this value, respectively. Vegetable residues represent 12.09% of the total potential biogas production in Jordan, with tomato and potato residues contributing 47.61% and 19.60% of this value, respectively [26]. Finally, Wang [95] found that residues from the major field crops contributed nearly 14.65%, with clover trefoil representing the highest contribution to this value at 68.9%. The digestion process for field crops is harder and more complex than animal manure because of the presence of cellulosic and lignocellulosic compounds that are difficult to hydrolyze [26]. Anaerobic co-digestion (ACOD) has attracted an increasing amount of attention over the last few decades due to its potential to increase biogas productivity from various organic wastes such as food and sewage sludge [96]. The co-digestion of animal manure/poultry or sewage sludge together with energy crops residues can improve the anaerobic digestion process by ensuring that the reactor maintains an optimal C/N ratio, providing a better nutrient balance for the bacteria and reducing nitrogen concentrations, which consequently reduces the risk of ammonia inhibition. Al-Hamamre et al. [26] found that MSW could potentially contribute 20.8% of the total biogas production in Jordan. The MSW collected from the northern, central, and western regions of Jordan represent 68.94%, 20.53%, and 10.53% of potential MSW biogas production, respectively. MSW has a high calorific value and can be used in refuse-derived fuels (RDFs). These fuels can be used in boilers, as well as in other infrastructure such as brick, paper, and iron kilns. MSW digestion can produce biogas at a rate of about 100–200 m^3/ton. Al-Hamamre et al. [26] found that, assuming a thermal efficiency of 70%, biogas production in Jordan can produce a total of 2.34 TWh of thermal energy. The biogas produced can be used to generate heat using a direct combustion process—this can be converted to mechanical energy using a combustion engine and further converted to electrical energy via an electrical generator. It can also be further refined into high-quality natural gas, which can be incorporated into the natural gas energy grid, especially in cities such as Amman and Aqaba. Al-Hamamre et al. [26] found that agriculture residues, MSW, and animal waste represented 38.76%, 35.18%, and 26.08%, respectively. In Jordan, MSW is considered to be the most promising biomass resource for the production of biogas due to the readily available infrastructure and transportation facilities. Malkawi et al. [47] note that, while some biogas plants are more expensive than others, most biogas plants are relatively simple and do not have noticeably high capital costs [82]. Arthur et al. [97] concluded that the effluent produced by biogas digesters could be used as organic fertilizer. Jafar and Awad [73] also found that biogas production could have several socio-cultural benefits, such as removing unpleasant odors and reducing organic waste. Furthermore, Aggarangsi et al. [98] noted that biogas energy systems have numerous environmental advantages, and have tangible environmental benefits such as reducing the environmental impact of GHG emissions and increasing the amount of biological slurry in the soil. Al-Hamamre et al. [26] showed that biogas production could account for nearly half of Jordan's total electricity consumption in 2012 (16,595 GWh). Jordan's natural resources could produce about 313.14 MCM of biogas, which can be converted into 573.81 GWh of power, subject to the energy availability factors and power conversion efficiencies. Figure 7 depicts the proportion and potential production of important biomasses in this scenario.

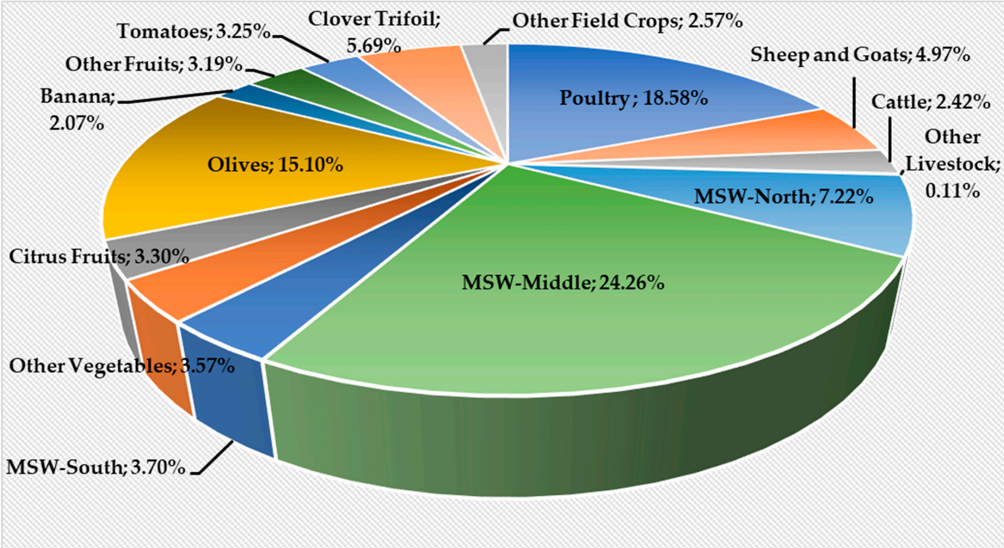

Figure 7. The contribution of significant biomass resources to yearly biogas production is also their potential for power generation.

6.2. Electricity Generation from Biomass

Electricity generation in the present day is heavily reliant on fossil fuels. Emissions from traditional thermal power plants reduce the air quality and have a strong contribution to the greenhouse effect. Farmers burn most agricultural residues in open fields, which releases toxins and dioxins while also squandering the heat generated [91]. Biomass accounts for 8.5% of total global energy usage, making it the fourth most important source of energy [99]. Obernberger and Thek [100] evaluated three decentralized biomass combined heat and power (CHP) plants with respect to their technology and economic feasibility. These plants are located in (1) a 4.4 MW_{el} Rankine cycle steam turbine in the Danish town of Assens; (2) a 4.1 MW_{el} Rankine cycle steam turbine in an Austrian sawmill; and (3) a 1.1 MW_{el} organic Rankine cycle (ORC) steam turbine located in Lienz, Austria [100]. An economic evaluation of a small-scale electricity generation project that utilizes biomass from agricultural forest sources in the Green Triangle has also been reported. Based on these investigations, a biomass feedstock with a plant gate expense of up to USD 29.6/ton is needed for biomass-fired power plants to be feasible and competitive with coal-fired plants [100]. Sagani et al. [94] found that a wood pellet-fired power plant with a power capacity of about 180 MW_{el} in Ghent, Belgium could provide electricity for about 320,000 homes, reducing the country's CO_2 emissions by 1200 kilo-tons. A study on the potential electricity generation from directly combusting dried tree pruning residues (olive and orange trees) with and without pressed olive kernels was conducted in Greece from a technological, economic, and environmental perspective [91]. Based on the literature, Al-Hamamre et al. [26] concluded that employing such technology in Jordan could be promising based on energy independence and environmental perspectives, with the combustion of various biomass resources capable of providing up to 2317 GWh of electricity.

7. Potential Biomass Production and Discussion

Between 2014–2019, agricultural byproducts and animal waste in Jordan were approximated to be available at a rate of 1284.2 kilo-tons/year and 10,909.6 kilotons/year, respectively (Table 7), which summarized the Jordan biomasses wastes, animal manure, and MSW, also its energy values. The potential power that can be generated from this waste via biogas generation is 816.2 MCM; animal manure represents 61.1% of this amount (Equations (4) and (5)). Assuming a thermal efficiency of 70%, biogas production in Jordan could potentially generate around 4.8 TWh of heat energy. The direct combustion of various biomass residues could provide Jordan with 2316.7 GWh of electricity, with animal waste, MSW, and agricultural residue contributing 46.48%, 40.13%, and 13.39% of this energy, respectively (Equation (6)).

Table 7. Comparison of the assessment results of various biomass resources in Jordan.

Biomass Resources							
Type	**Dry Waste Yield**	**Availability Factor of Energy**	**Heating Value**	**Energy Content Based on Theoretical**	**Electricity Generation Based on Theoretical**	**Production of Biogas**	**Electricity Generation from Biogas**
	(kton)	**(-)**	**(MJ/kg)**	**(TJ/kg)**	**(TJ)**	**(MCM)**	**(GWh)**
Residues of Vegetables	226.7	0.25	6.0	340.0	19.5	21.8	35.7
Residues of Fruits	940.3	0.25–0.75	13.0–17.4	5981.1	350.7	137.3	224.9
Residues of Crops	117.2	0.25	14.7–18.6	519.8	29.7	7.6	12.4
Animal Manure	10,909.6	0.125–0.90	13.5–17.8	112,968.4	3403.8	498.6	440.7
MSW	3900	0.75	11.49	16,356	954.1	150.9	247.2
Total	16,093.8	-	-	136,165.3	4757.8	816.2	960.9

The total potential energy that can be produced from crop residues can be calculated using the following equations:

$$C_B = C_F \times R_F \times W_F \times A_F \quad (1)$$

where C_B is the collected dry biomass (kg/year), C_F is the yearly production of crops (kg/year), R_F is the residue factor, W_F is the proportion of dry weight, and A_F is an availability factor [101,102].

$$E_P = C_B \times O_C \times HHV \quad (2)$$

where E_P is the potential energy from the crop residue (MJ), O_C is the organic content, and HHV is the higher heating value of available residue (MJ/kg) [103].

The HHV (MJ/kg) can be calculated through the following equation:

$$HHV = 1.3675 + 0.3137 \times C + 0.7009 \times H + 0.0318 \times O \quad (3)$$

where C is the carbon content, H is the hydrogen content, and O is the oxygen content [101,102].

Based on Equations (1)–(3), residue from Jordanian crops could have an energy density as high as 519.8 TJ/kg.

Energy production from animal manure can be calculated through the following equations [23]:

$$B_P = H_N \times C_S \times V_F \times X_F \times B_E \quad (4)$$

$$E_P = B_P \times M_F \quad (5)$$

where B_P is the biogas potential of animal manure (m^3/day), H_N is the animal heads, C_S is the solid concentration, V_F is the daily volatile solids content (kg/head/day), X_F is the recovery factor of the system (0.20), B_E is the yield of obtained biogas per kilogram of volatile solid (constant; 0.22 m^3/kilogram total solid (kgts)) [104], E_P is the potential amount of energy generated daily (GJ/day), and M_F is the methane conversion factor (constant; 0.036 GJ/m^3) [104].

The potential electricity that can be obtained from various biomass feedstocks by gasification, combustion, and pyrolysis can be calculated through the following equation:

$$P_e = \frac{\eta_c \eta_e m_i H_{vi}}{3.6 \times 10^6} \quad (6)$$

where P_e is the annual potential generation of electricity (GWh/year), m_i is the annual mass of available residue (kg/year), H_v is the heating value of the available biomass (MJ/kg), η_c is the efficiency of the conversion process, and η_e is the efficiency by which thermal energy can be converted to electrical energy [25].

8. Challenges

Jordan faces many challenges in its attempts to utilize biomass resources. First, the potential energy that can be generated from animal manure and food waste is underutilized. Furthermore, biomass resources such as agricultural waste, as well as trees and wood residues, are spatially dispersed, making harvesting and gathering these materials difficult. The dispersed distribution of these resources is a significant barrier to the success of biomass-based power plants, resulting in high labor, gathering, transportation, and storage costs. These costs can be reduced through proper management, planning, and the establishment of biomass collection points for biomass energy conversion plants. Second, Jordan's use of the biomass, agriculture, and stockbreeding industries is relatively small and inadequate. To overcome this obstacle, funds must be raised for pilot plant facilities based on viable, well-developed business models; these plants can be used to generate energy from organic biomass in an economically feasible manner. Third, Jordan does not currently have a comprehensive solid waste management plan that takes recycling, energy generation, and environmental aspects into account. Jordan's waste management system is experiencing several significant challenges, including a lack of financial assistance, a lack of appropriate tools, and the absence of laws that govern the involvement of the private sector, which impedes the development of MSW management initiatives. Farmers and livestock owners should be financially incentivized to help with this by purchasing their organic biomass wastes and using locally generated biomass waste at low prices. Fourth, there is a lack of research and development in the field of high-energy-density biomass products due to the lack of well-equipped biomass research laboratories in Jordan. Furthermore, these landfills built for MSW disposal are often not regarded as engineering landfills (with the notable exception of the Ruseifah and Al Ghabawi landfills) [26]. Thus, good government policies and well-executed strategic initiatives for the utilization of renewable resources are sorely needed for these energy sources to be feasible in Jordan [28].

Finally, biomass resources have the potential to be viable and feasible in Jordan. Jordan's government could also assist by providing incentives for locals to manage biomass efficiently, monitoring abundant biomass supplies, and encouraging heating device manufacturers to concentrate on biomass studies. The achievement of any biomass project is strongly reliant on the understanding of communities regarding the advantages and importance of using biomass feedstocks such as agricultural residues to obtain alternative fuels and generate electricity.

9. Conclusions

Biomass has emerged as one of the most important renewable sources of energy worldwide. Despite the availability of various biomass sources in Jordan, these resources have not been optimally utilized to develop and enhance the Jordanian energy sector. This work investigates the present state and potential of using biomass as a source of energy in Jordan. This study evaluated the available quantities of biomass that can be obtained from agricultural residues, animal manure, and MSW based on raw material estimates collected between 2014 to 2019 in conjunction with standard parameters obtained from the literature. This work finds that Jordan generates a sustainable amount of biomass, primarily from agricultural residues and animal wastes. Biomass can be converted into electrical and thermal energy, as well as biogas. These findings show that biomass residues could play an important role in Jordan's energy mix. Between 2014–2019, animal manure and agricultural waste were estimated to be available at a rate of 10,909.6 kilo-tons/year and 1284.2 kilo-tons/year, while MSW was generated at a rate of 3900 kilo-tons/year. The estimated total energy of agricultural crop residues was found to be 519.8 TJ, and the amount of biogas that could be generated annually was 816.2 MCM (equivalent to 960.9 GWh), with animal manure accounting for 61.1% of this amount. This is equivalent to approximately 5.1% of the total electricity consumption in Jordan in 2019 (18,853 GWh). MSW accounts for 18.5% of Jordan's total potential biogas production. Due to the availability of developed infrastructure and transportation facilities in Jordan, MSW is considered to be the most promising biomass resource for biogas generation in Jordan. Furthermore, the biogas generated could be injected into the natural gas distribution system in cities such as Amman and Aqaba.

Depending on the policies enacted and the strategies executed by the Jordanian government, there can be adequate investment in the biomass industry, accelerating the adoption of biomass-derived energy. The Jordanian government can play a significant role in driving biofuel research and growing interest in biomass resources by raising people's understanding of the significance of biomass as a source of energy. It can also organize advanced training programs and provide the required expertise and equipment to prepare for the skilled labor required to develop advanced biomass practices and technologies. In addition, the Jordanian government should consider other incentives, such as finding ways to subsidize the cost disadvantage of the biomass production chain compared to carbon fuels by establishing regulations that encourage the consumption and production of biomass, such as fuel tax incentives, the establishment of trading, and financial incentives for farmers' cooperative associations. The government could also implement feed-in tariff schemes to spur investment in the biomass energy sector, as well as inspire the private sector to adopt related projects. The government can also help by incentivizing locals to handle their biomass resources effectively, monitoring available biomass feedstocks, and encouraging heating device manufacturers to concentrate on biofuel studies.

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