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Research Article

Bioenergy Production Potential of Available Biomass Residue Resources in Ethiopia

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The study intends to present the bioenergy potential in Ethiopia using major sources of biomass generation. The study utilized data from secondary sources to generate the potential using the available biomass sources within the country. In order to determine the bioenergy potential, four residue biomass sources, including livestock manure, crop residues, forest residues, and municipal solid waste (MSW) from major cities, were considered. The Food and Agriculture Organization Corporate Statistical (FAOSTAT) Database as well as national and local reports were used to compile information on crops, forests, animals, and human populations. The potential of each source is estimated for 2020-21 as the base year. The total bioenergy potential of the country is estimated to be 2955 petajoule (PJ) per year, with 56.01% of it coming from forest residue, 28.29% from crop residue, 15.36% from livestock waste, and 0.33% from MSW. In addition, it is estimated that 819.7 terawatt hours (TWh) of electricity may be generated from all sources yearly. This is equivalent to around 8, 58, and 89 times Ethiopia's total primary energy consumption, electricity production, and electricity net consumption in 2020, respectively. Results also demonstrated that the total potential (819.7 $TWh{\cdot}y^{-1}$) is roughly 56% greater than the forest residues' potential alone (459 $TWh{\cdot}y^{-1}$). This implies that biomass resources might be crucial in assisting Ethiopia to fulfill its future energy needs. To fully realize the availability of biomass energy, the study suggests performing integrated development research, choosing the best feedstock and value chains for bioenergy, and creating a bioenergy database.

1. Introduction

The amount of future bioenergy depends heavily on available biomass resources in addition to their long-term utilization [1]. In 2018, fossil fuels provided around 85% of the primary energy used worldwide [2, 3]. Biomass conversion to electricity increased from 65 GW in 2010 to 120 GW in 2019, and factors such as low energy prices, more distributed generation, and environmental and climate change concerns all played a role [2]. Reduced reliance on fossil fuels and their adverse impact on global warming are the driving forces behind the desire to move to biomass energy, which is proposed to be relatively clean [4].

Biomass has the potential to replace traditional fossil fuels in the energy sector as it is a clean, renewable energy source [5]. Biomass resources are classified as agricultural wastes (crop and animal residues), forest residue biomass, waste biomass, and aquatic biomass [6, 7]. By 2050, bioenergy produced from biomass will be needed at a rate of 77–155 EJ per year, while the need for synthetic biomaterials will be approximately 20 EJ per year. Bioenergy will account for 15% of the world's energy consumption by 2050 or 130–270 EJ per year [6, 8]. Globally, biomass contributes 9–15% of total energy [9–11]. In developing countries, about 75–90% of the population uses biomass as a source of energy [6].

Most biomass, such as crop residues and forest residues, which is a major source of atmospheric pollution, in sub-Saharan Africa is burned [6, 12]. Every year, 2–5 Pg (10^{15} g) of carbon is estimated to be burned in the form of biomass around the world [13]. These estimated carbon emissions range from 1/5th to 1/3rd of those caused by the combustion of fossil fuels [13]. In terms of traditional energy generation, biomass is the most important source, accounting for over

89% of the country's total energy supply [14]. Households utilize nearly 88% of total energy consumption, while the transportation, industrial, and telecommunications and service sectors use 3%, 40%, and 5% of total energy, respectively [14–16]. This primarily takes the form of charcoal, firewood, and animal dung. Biomass resources are primarily used by direct burning in open fire systems in sub-Saharan countries including Ethiopia, which causes indoor air pollution and contributes to health problems, particularly for children and women due to direct exposure to the risk [12]. Biomass derived from crop residues, animal wastes, forest residues, and MSW are good sources of bioenergy and can greatly contribute to the production of bioenergy in the country. For a number of reasons, Ethiopia is interested in modern bioenergy, including energy supply security, socioeconomic benefits to rural communities, the creation of new revenue streams, and cost savings from reduced crude and refined oil importation.

The majority of the energy in Ethiopia comes from biomass, and it has one of the lowest rates of access to contemporary energy services. Ethiopia is among the countries facing energy poverty around the world, making alternative energy resources development feasible [17] in which a direct link exists between lack of energy and poverty [18]. Alternative energy utilization will enhance lifestyles and enable economic sustainability [19]. Even by African standards, Ethiopia has one of the least diverse energy sectors in the continent [20]. Ethiopia is among the countries with the lowest per capita energy supplies and consumption rates in the world [16, 21, 22]. In comparison to the global average of 1.9 ton(s) oil equivalent (toe), the primary energy supply per person is approximately 0.4 toe [16], while primary energy consumption per person is approximately 0.07 toe [16, 22]. The three main energy sources in the country are biomass bioenergy (approximately 88%), petroleum fuel (approximately 10%), and hydropower electricity (approximately 3%) [16, 23].

The concept of using biomass for decentralized energy production is quickly gaining attention in the worldwide energy industry. In rural and remote areas, access to modern energy is extremely difficult in most developing countries, including Ethiopia, from an economic standpoint. Direct power connections to rural areas place a significant burden on developing countries, which already have many constraints [24]. Modern energy implementation's primary goals are to reduce massive deforestation and forest degradation [25–27], indoor and outdoor pollution [28, 29], GHG emissions [30–33], enhance health quality [34–36], and provide socioeconomic benefits [37]. GHG emissions from fuelwood burning are also affected by a number of factors, including fuel type, cooking method, fuel consumption, and cooking time [28]. Modern fuels can be utilized in place of fossil fuels and conventional biomass fuels to minimize GHG emissions during energy production and combat climate change [38]. Furthermore, Ethiopia's regulatory policies in support of modern bioenergy are becoming more prevalent. However, as previously stated, Ethiopia's use of bioenergy has seen very little progress. Several studies [7, 39–42] have highlighted the lack of data, particularly on resource availability, as a significant challenge to Ethiopia's adoption of modern bioenergy.

Two approaches can be used to estimate biomass resources: demand-driven and/or resource-focused approaches [7]. For assessing biomass and bioenergy potential, the most commonly used approach around the world is the resource-based approach. This method takes into account particular biomass types, such as residues from forest and agricultural, and their processing byproducts [8, 43]. As a result, this study presents the biomass resource assessment in Ethiopia using the resource-focused approach and multiple sources' data.

Therefore, the objective of this study is to evaluate if available residue biomass resources in Ethiopia are sufficient to provide enough contemporary energy and make bioenergy production viable and sustainable. The study's primary objective is to quantify the total quantity of available biomass resources in Ethiopia and corresponding recoverable biomass that can be converted into bioenergy. Four main residual biomass sources, livestock manure, crop residues, forest residues, and municipal solid waste (MSW) in Ethiopia's major cities, were taken into account when calculating the bioenergy potential.

2. Methodology

The overall approach employed in this paper is described in this section in order to evaluate the potential of the biomass resources studied, which can be divided into four categories: (i) municipal solid waste (MSW), (ii) animal manure, (iii) agricultural crop residues, and (iv) forest residue biomass. Annual production data for the base year 2020-2021 were derived from the population census [44], livestock statistics of Ethiopia [45], crop statistics (agricultural sample survey data) for major crops [46], and forest biomass [47].

2.1. Municipal Solid Wastes (MSW). The 2007 Ethiopian national census served as the source for the population statistics [44] and projected to 2020 using the population growth rate. The population increased at an average of 2.73% annual rate during the period 2007–2020 [48]. This rate was applied to calculate population figures for 2020. For MSW generation estimation, this study primarily considered towns across the country where large amounts of MSW are generated and can be collected, transported, and processed. This is due to the fact that waste generation is minimal in rural settings (less than 150 g per person per day). To estimate MSW generated yearly and bioenergy potential, around 0.5 kilogram per person per day of MSW generation was assumed on average per person [7]. This was according to the average assessments performed in the country's major towns, including Addis Ababa (0.4 kg per person per day), Gondar (0.45 kg per person per day), and Jimma (0.65 kg per person per day). When estimating bioenergy, it was assumed that each ton of waste contained roughly 4.5 GJ of energy and that 90% of the waste consisted of biomass that was not separated throughout the energy conversion [49]. The total amount of MSW generated in 2020 and the corresponding potential bioenergy available are estimated using the population growth rate equation (1) used by Mehta [50] and the method developed for bioenergy potential estimation equation (2) [7],

$$P_{2020} = P_{2007} \times \left(1 + \frac{r}{100}\right)^n, \quad (1)$$

where P_{2020} is the projected future value, P_{2007} is the past value, n is the projected number of years, and r is the population growth rate.

The potential bioenergy from MSW is estimated using the following equation:

$$\mathrm{BEP}_{(\mathrm{MSW}i)} = (365\ \mathrm{days}) \sum_{i=1}^{n} \left(N_{(i)} \times Q_{(i)} \times P_{(i)} \times \mathrm{LHV}_{(i)}\right), \quad (2)$$

where $\mathrm{BEP}_{(\mathrm{MSW}i)}$ is the potential bioenergy from MSW at location i^{th}, $N_{(i)}$ is the human population in i^{th} town, $Q_{(i)}$ is the MSW amount generated per person per day at i^{th} town, $P_{(i)}$ is the MSW percentage collected at i^{th} town, and $\mathrm{LHV}_{(i)}$ is the lower heating value of collected MSW from i^{th} town.

2.2. Animal Manure. Animal manure is an important component in the bioenergy generation owing to its composition (energy value). The current study estimates the potential of animal waste biomass resources for energy production using locally available animal production in the country. The assessment took into account manure waste from only six different types of farm animals. This is due to the fact that these animal types are the most common ones that are raised by many households in Ethiopia, as the Central Statistical Agency (CSA) of Ethiopia has also stated. The animal effluents energy potential was estimated using excreta from cattle, sheep, goats, horses, donkeys, and poultry. Because of animal weight and size variations, as well as feed intake, livestock waste generation varies by country and region within a country [51, 52]. To estimate the energy potential of livestock effluents, some indicative values of waste parameters relevant to animal waste, such as the number of animals, daily manure generation per animal, and energy value per animal type, were collected from the literature. The average values were then utilized to calculate the amount of bioenergy that each animal category waste can generate, as the bioenergy yield of a specific animal category waste is dependent on the dry matter organic fraction in the livestock waste and the associated waste management system.

Equation (3) [7, 52, 53] is employed to calculate the available bioenergy potential from recoverable animal effluent biomass that can be collected for energy application.

$$\mathrm{BEP}_{(Aij)} = 365 \sum_{i=1}^{n} N_{(ij)} \times DM_{(i)} \times \eta_{(i)} \times LHV_{(i)}, \quad (3)$$

where $\mathrm{BEP}_{(Aij)}$ is the bioenergy potential at location j^{th}, $N_{(ij)}$ is the number of animals of i^{th} species at location j^{th}, $\mathrm{DM}_{(i)}$ is the dry matter per head per day for i^{th} animal species, $\eta_{(i)}$ is the collection efficiency of i^{th} animal dung, and $\mathrm{LHV}_{(i)}$ is the i^{th} animal dung lower heating value.

2.3. Crop Residues. Agricultural crop residual biomass availability can be estimated using crop statistics from the Ethiopian Statistics Service (ESS) Database [46]. Major crop types were estimated using crop statistics from the Central Statistical Agency of Ethiopia for the year 2020-21. In this study, 44 residues from 30 important crops were taken into account. The residue types (straw, stalk, husk, peelings, pod/shell, pruning, leaves, and so on) of the considered crops as well as the recoverable fraction (RF), heating values (HV), and the residue-to-product ratios (RPR) for each crop studied were detailed in the results section. Crop residue is a byproduct of crop cultivation and processing. While the recoverable residue potential refers to the residue that is left over after competing uses, the gross residue potential refers to the total amount of residue generated. The useable or recoverable fraction can be converted into bioenergy. Standard methods are used to calculate the gross and recoverable potentials [39, 54–56].

A particular crop's gross residue potential is defined by the cultivated area, crop production, and RPR. Crop residue generation differ even more than crop productions and are therefore challenging to account for, as they are influenced by plant variety, location, farming practices, climate conditions, and other factors [57]. As a result, the relevant literature's RPR values for different crops were compiled, and the average value for each crop residue type was used for the estimation. Equation (4) was employed to compute the crop residue gross potential:

$$\mathrm{GRP}_{(j)} = \sum_{i=1}^{n} A_{(i)} \times CY_{(i)} \times \mathrm{PRP}_{(i)}, \quad (4)$$

where $\mathrm{GRP}_{(i)}$ is the gross residue potential at location j^{th} from n numbers of crops, $A_{(i)}$ is the area of crop i^{th} at j^{th} location, $CY_{(i)}$ is the average crop yield of the crop i^{th} at j^{th} location, and $\mathrm{PRP}_{(i)}$ is residue-to-product ratio of the i^{th} crop at j^{th} location.

This analysis made the assumption that not all agricultural residue biomass would be suitable for bioenergy generation because of variations in nature and competing uses. The recoverability percentage of crop residual biomass (also known as the surplus availability factor) is employed to estimate field-based residue biomass resource collected realistically [6, 52]. The fraction of residues that can realistically be used for the production of bioenergy after some of it has been used elsewhere is known as the recoverability factor (RF) [6, 58, 59]. The RF values for biomass residue were gathered from previous studies of a similar nature conducted in other countries because there was a lack of data especially for Ethiopia. The average value was used to evaluate the potential for recoverable residue for each type of crop residue. To compute the recoverable residue potential, equation (5) is employed:

$$\mathrm{RRP}_{(j)} = \sum_{i=1}^{n} \mathrm{GRP}_{(ij)} \times RF_{(ij)}, \quad (5)$$

where $\mathrm{RRP}_{(j)}$ is the recoverable residue potential at location j^{th}, $\mathrm{GRP}_{(ij)}$ is the gross residue potential at location i^{th} from n number of crops, and $RF_{(ij)}$ is the recoverability factor of i^{th} crop at j^{th} location.

Using equation (6), the biomass of crop residues' potential for bioenergy generation is calculated as follows [39, 56]:

$$\mathrm{BEP}_{(Cj)} = \sum_{i=1}^{n} \mathrm{RRP}_{(ij)} \times \mathrm{LHV}_{(ij)}, \quad (6)$$

where $EP_{(Cj)}$ is the bioenergy potential of n crops at j^{th} location, $\mathrm{RRP}_{(ij)}$ is the recoverable residue potential of i^{th} crop at j^{th} location, and $\mathrm{LHV}_{(ij)}$ is the lower heating value of i^{th} crop at j^{th} location.

2.4. Forestry Residues. Forest biomass residue resources are generally divided into two types: logging residues and wood-processing residues. During the harvesting process, logging leftovers such as roots, branches, leaves, stumps, tops, and sawdust are produced. Plywood and sawmill-processing activities generate wastes biomass from wood processing, for example, barks, woodchips, sawdust, rejected logs, and offcuts [60–62]. The majority of logging operations produce logging residues, which make it challenging to collect the residues for energy consumption. Such leftover wastes are typically left in forests for a number of reasons, which include logistics and the low demand for fuel (with high moisture content) in such places [62]. Not all forestry leftovers can be used as feedstock for bioenergy production. The amount of forest residues that can be collected for energy generation is constrained by technical, ecological, and environmental considerations [61]. Logging and wood-processing residue recoverability fractions are used to calculate the amount of residues from logging and wood processing that can be practically collected. The proportion of logging and wood-processing residues that can be harvested and recovered for the generation of energy is assumed to be around 25% and 42% in developing countries [63]. The approach proposed by Smeets [60] for estimating forest residue bioenergy potential was employed in this study.

The bioenergy potential of logging residue was estimated using the following equation:

$$\mathrm{BEP}_{\mathrm{LR}} = \sum_{i=1}^{n} \left(W_{\mathrm{i}} \times h \times H \times \mathrm{LHV}\right), \quad (7)$$

where BEP_{LR} is the energy potential of logging residues and W_i is the annual round wood production of classification i^{th}. For the logging residue, the generation ratio factor h was 0.6 [52, 60] and the recoverability fraction factor of the logging residue represented by H is predicted to be around 25% in developing nations [63]. For forest residue, the lower heating values were obtained from previously published data [52].

Using equation (8), the bioenergy potential of wood-processing residue was estimated.

$$\mathrm{BEP}_{\mathrm{PR}} = \sum_{k=1}^{n} \left(\mathrm{IRW}_i \times p \times P \times \mathrm{LHV}\right), \quad (8)$$

where IRW is the annual consumption of industrial round wood of category i^{th} and $\mathrm{BEP}_{\mathrm{PR}}$ is the energy potential of wood-processing byproducts. Factor p is the percentage of logs that are changed into residues throughout the wood-processing process, and it is impacted by how efficiently sawmills function. As stated in [52], a p value of 70% is used for developing countries. The portion of processing residues that can realistically be made accessible for the generation of bioenergy is known as the recoverability fraction P of wood-processing residues. Estimates from developing countries place factor P at around 42% [63].

3. Results and Discussion

3.1. Biomass Resources' Potential. This paper calculates Ethiopia's potential for producing bioenergy from various feedstock sources. An estimate of the studied biomass residue resources and the corresponding bioenergy potential are detailed.

3.1.1. Municipal Solid Wastes (MSW). About 2168 million kg of municipal solid wastes can be produced annually in the country's biggest cities and regions. It is possible to use these waste biomass resources to produce bioenergy. The total bioenergy potential from MSW of Ethiopia's big cities has been estimated to be 9.76 $\mathrm{PJ \cdot y^{-1}}$. Table 1 shows that the share of capital cities in Oromia and Addis Ababa city was 31% and 26% of the total energy, respectively.

The estimates of this study seem to be slightly higher than those of earlier studies. Since the population growth rate used in the current study was projected population data to 2020, a higher potential was anticipated from the outset. For instance, based on population statistics from 2007, Gabisa and Gheewala [7] calculated that the gross bioenergy potential of MSW was around 3.8 $\mathrm{PJ \cdot y^{-1}}$. Moreover, only a few significant Ethiopian cities, including Addis Ababa, Adama, Arba Minch, Assela, Bahir Dar, Bishoftu, Debre Markos, Dessie, Dire Dawa, Gondar, Hawassa, Mek'ele, Nekemte, and Woldia, were taken into account in their study.

3.1.2. Animal Residue. The most prevalent animals in Ethiopia are cattle, goats, sheep, horses, donkeys, and poultry. The estimated gross animal manure generation from the six categories is 76944 $\mathrm{ktDM \cdot y^{-1}}$ in Ethiopia. The estimated recoverable animal manure is about 29598 $\mathrm{ktDM \cdot y^{-1}}$. This indicates that 38% of the gross residues in the country is recoverable. Cattle contribute the most manure on an individual basis. Agricultural farmers are mostly located in rural areas, where they can let their livestock roam freely during the day. It is possible to use the recoverable residue biomass resources to produce modern energy. Cattle account for roughly 74% of the estimated total recoverable bioenergy potential from animal residue, which is 454 $\mathrm{PJ \cdot y^{-1}}$ (see Table 2).

Table 1: Estimated municipal solid wastes generation and bioenergy potential.

Geographical area	Population (million)[a]	Waste generated (million·kg·y^{-1})	Potential bioenergy (PJ·y^{-1})
Oromia region	3.33	608	2.73
Addis Ababa city administration	2.75	502	2.26
Amhara region	2.12	387	1.74
S.N.N.P region	1.50	274	1.23
Tigray region	0.85	155	0.70
Somali region	0.63	114	0.51
Dire Dawa city administration	0.23	43	0.19
Afar region	0.19	34	0.15
Benishangul-Gumuz region	0.11	19	0.09
Harari region	0.10	18	0.08
Gambella region	0.08	14	0.06
Total			9.76

[a]Projected population data in cites only.

Table 2: Estimated animal residue generation and bioenergy potential.

Livestock	Production (million)	Dry dung (kg·d^{-1})[a]	Collection efficiency (%)[b]	LHV (GJ·t^{-1})[c]	Gross manure (ktDM·y^{-1})	Amount of dry matter recoverable (ktDM·y^{-1})	Potential harvestable bioenergy (PJ·y^{-1})
Cattle	70.29	1.86	43	16.7	47636	20245	337
Sheep	42.91	0.37	32	14.0	5819	1852	26
Goat	52.46	0.42	29	14.0	8065	2299	32
Horses	2.15	3.15	31	12.0	2470	766	9
Donkey	10.79	3.00*	31	11.0*	11817	3663	40
Poultry	56.99	0.05	68	11.0	1137	773	9
					76944	29598	454

[a]Dry dung data were obtained from [6, 7, 24, 52, 55, 59] for cattle, sheep, goat, and poultry and from [7, 52] for horses. [b]Collection efficiency data were obtained from [6, 7, 52, 55, 59, 64] for cattle, sheep, and goat, from [7, 52, 64] for horses, from [64] for donkey, and from [6, 7, 52, 55, 59] for poultry. [c]LHV data were obtained from [6, 7, 24] for cattle, sheep, goat, and poultry and from [7, 65] for horses. *Author assumption.

This is due to the country's high cattle population, which according to [7] ranks fifth in the world and leads to high cattle waste recovery. In addition, the majority of Ethiopian households reared cattle as a part of their farming system. The Ethiopian national economy and the means of subsistence for many Ethiopians both benefit greatly from the livestock subsector. The livestock industry contributes about 16.5% of the nation's GDP and 35.6% of the agricultural GDP [66]. The country has a wide variety of livestock. Although some business owners also produced goods for sale, farmers make up the majority of the country's producers. Despite the fact that the animals are owned by different households, they move around the area during the day to graze in common areas before returning to their owners at night [7]. The efficiency of residue collection is consequently poor.

3.1.3. Crop Residue. The total gross crop residue generated by 30 different crops is estimated to be 88041 kt per year. In Ethiopia, maize residues account for the majority of the individual crop residues (24506 kt), followed by sorghum (20753 kt) and teff (12673 kt). Of the total gross crop residue generated above, 65% of the gross residue is available as recoverable for bioenergy generation. The estimated total recoverable bioenergy potential from recoverable crop residues is about 836 PJ per year, with maize accounting for 37% (308 PJ per year) and sorghum accounting for 29% (243 PJ per year) at an individual crop level, see Table 3.

This is because many small family farmers also grow maize, a staple grain, in addition to commercial farmers. At the individual crop group level, the cereal crop group accounts for about 682 PJ·y^{-1}, followed by fruit crops and root crops, which account for about 60 PJ·y^{-1} and 46 PJ·y^{-1}, respectively. Other important crops in Ethiopia include coffee, pulses, oil seeds, sugarcane, and vegetables, which contribute about 17 PJ·y^{-1}, 12 PJ·y^{-1}, 10 PJ·y^{-1}, 9 PJ·y^{-1}, and 1 PJ·y^{-1} respectively. This demonstrates that the cereal category makes for about 81.6% of the overall recoverable bioenergy potential from crop residues.

3.1.4. Forest Residues. Forest residue estimates and bioenergy potential are shown in Table 4. The total recoverable bioenergy potential of the forest residue in Ethiopia is estimated to be about 1654 PJ·y^{-1}.

Fuelwood contributes about 1490 PJ·y^{-1} (90%) of the total bioenergy from forest residues, followed by charcoal wood (139 PJ·y^{-1}). This is because only 2,917 hm^3 of round wood are produced for industrial use, whereas 107,963 hm^3 of round wood are used as wood fuel (firewood). The country's economic growth has accelerated. Consequently, the rate of deforestation has dramatically increased. The FAO (2013) report, which was mentioned in [7], states that the Ethiopian government has recently taken into account the restoration of these forest resources, which are currently estimated to be 10%–30%.

Table 3: Estimated crop residues and bioenergy potential.

Crop group	Crop type	Type of residue	Production amount (kt)[a]	RPR (dimensionless)[b]	RF (dimensionless)[b]	LHV ($MJ\cdot kg^{-1}$)[b]	Total amount of residue (kt)	Recoverable amount of residue (kt)	Potential bioenergy ($PJ\cdot y^{-1}$)
Cereals	Maize	Stalk	10,557	1.7	0.8	14.7	18,128	14,502	212.56
		Husk	10,557	0.2	1.0	14.1	2,191	2,191	30.84
		Cob	10,557	0.4	1.0	15.4	4,187	4,187	64.60
	Wheat	Straw	5,780	1.3	0.3	16.1	7,514	2,179	35.09
		Husks	5,780	0.3	0.3	15.1	1,532	444	6.73
	Teff	Residue	5,510	2.3	0.3	15.0	12,673	3,802	57.03
	Sorghum	Straw	4,517	1.7	0.8	12.4	7,890	6,312	78.15
		Stalk	4,517	2.8	0.8	16.0	12,863	10,291	164.65
	Barley	Straws	2,339	1.3	0.3	15.9	2,936	822	13.05
	Finger millet	Straw	1,203	1.5	0.6	14.5	1,845	1,015	14.67
	Rice	Straw	268	1.5	0.5	15.8	392	190	3.00
		Husk	268	0.3	0.8	17.4	71	58	1.00
	Oats/aja	Straw	31	1.4	0.3	13.7	43	12	0.16
Pulses	Faba beans	Stems-leaves	1,071	1.5	0.2	15.2	1,552	233	3.54
	Lentils	Straw	113	1.7	0.2	14.7	196	39	0.57
	Soybeans	Straw	209	2.3	0.7	15.2	485	339	5.14
		Pods	209	1.0	1.0	12.4	209	209	2.58
Oil seeds	Sesame	Stalk	260	1.5	0.1	14.4	390	49	0.70
	Groundnut	Shells	205	0.4	0.9	17.6	82	77	1.35
		Straw	205	2.2	0.9	15.6	451	421	6.56
	Linseed	Stalk	80	1.5	0.5	14.4	118	59	0.85
	Rapeseed	Straw	13	1.6	0.2	14.6	20	4	0.07
	Safflower	Stalk	4	3.0	0.8	13.9	13	11	0.15
Vegetables	Red peppers	Residues	296	0.5	0.5	12.0	133	67	0.80
	Green peppers	Residues	74	0.5	0.5	12.0	33	17	0.20
	Tomatoes	Stem	42	0.3	0.5	13.7	13	6	0.09
		Leaves	42	0.3	0.5	13.7	13	6	0.09
	Lettuce	Waste	1	1.2	0.5	12.8	1	0	0.00
Root crops	Taro/godere	Peelings	2,328	0.3	1.0	10.6	652	652	6.92
		Straw	2,328	0.5	0.8	10.6	1,164	931	9.88
	Sweet potatoes	Leaves and peels	1,599	0.5	0.8	13.3	799	640	8.51
	Potatoes	Peelings	1,142	0.8	1.0	10.6	856	856	9.09
		Leaves	1,142	0.8	0.8	16.0	868	694	11.11
	Yam/boye	Peelings	46	0.2	1.0	10.6	10	10	0.11
		Straw	46	0.5	0.8	10.6	23	18	0.19

Table 3: Continued.

Crop group	Crop type	Type of residue	Production amount (kt)[a]	RPR (dimensionless)[b]	RF (dimensionless)[b]	LHV ($MJ \cdot kg^{-1}$)[b]	Total amount of residue (kt)	Recoverable amount of residue (kt)	Potential bioenergy ($PJ \cdot y^{-1}$)
Fruit crops	Bananas	Leaves	898	0.4	0.8	11.4	314	252	2.86
		Stem	898	5.6	0.8	12.4	5,031	4,025	49.82
		Peels	898	0.3	0.8	15.8	225	180	2.84
	Mangoes	Prunings	151	1.8	0.8	17.5	272	218	3.81
	Oranges	Prunings	40	0.3	0.8	18.1	11	9	0.16
	Lemons	Prunings	6	0.3	0.8	17.6	2	1	0.03
Other	Coffee, green	Husk	585	2.1	1.0	14.2	1,228	1,228	17.48
	Sugarcane	Baggase	1,345	0.2	0.7	19.0	312	230	4.35
		Topes/leaves	1,345	0.2	0.9	17.9	300	259	4.64
									836.03

[a]Obtained from the Ethiopian Central Statistical Agency (CSA) [46].

Table 4: Estimated forest residues and bioenergy potential.

Forest byproducts	Annual production	Unit	Residues	Recovery rate	Total residues (hm^3)	LHV ($GJ \cdot m^{-3}$)	Potential bioenergy ($PJ \cdot y^{-1}$)
Logging residues	2.917	hm^3	Solid wood	0.40[a]	1.167	7.40[c]	8.63
		hm^3	Dust	0.20[a]	0.583	7.40[c]	4.32
Wood-processing residue	2.917	hm^3	Sawdust	0.12[a]	0.350	8.40[c]	2.94
		hm^3	Solid wood	0.38[a]	1.108	8.40[c]	9.31
Plywood	0.024	hm^3	Solid	0.45[a]	0.011	8.40[c]	0.09
		hm^3	Dust	0.05[a]	0.001	8.40[c]	0.01
Particle board	0.022	hm^3	Dust	0.10[a]	0.002	8.40[d]	0.02
Fuelwood	107.963	hm^3	—	1.00[b]	107.963	13.80[b]	1,489.89
Sawdust and wood chips	0.023	hm^3		0.90[a]	0.020	14.55[b]	0.29
Wood charcoal	4.222	tons	—	1.00[a]	4.222	33.00[b]	139.31
Total							1,654.82

[a]Data were obtained from [67]. [b]Data were obtained from [52]. [c]Data were obtained from [68]. [d]Author assumption.

Table 5: Total energy potential of Ethiopia's biomass residue resources.

Energy source	Energy potential (PJ·y^{-1})	Energy potential (TWh·y^{-1})
Crop residues	836	232
Animal manure	454	126
Forest residues	1655	459
MSW	9.76	2.7
Total	2954.76	819.7

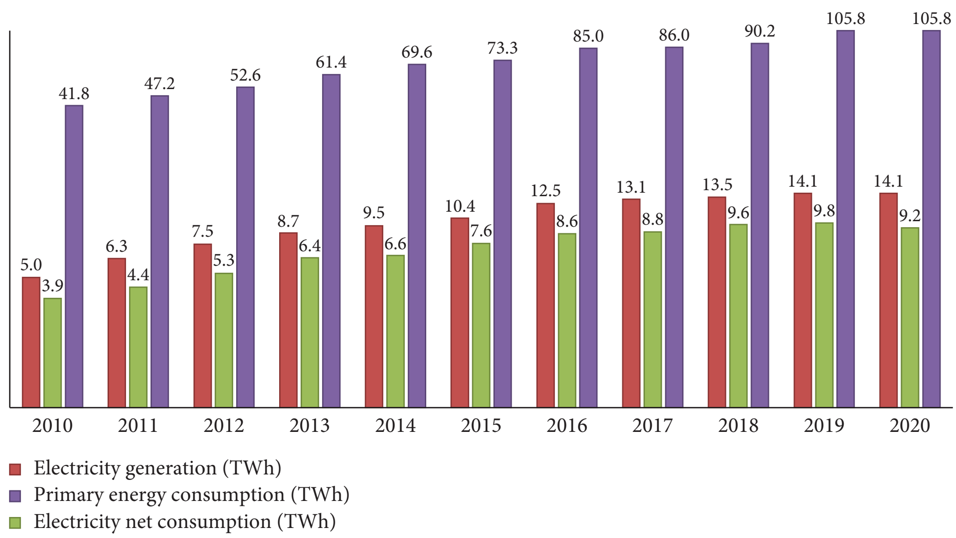

Figure 1: Electricity generation, consumption, and primary energy consumption for the years 2010–2020 [21, 40].

3.2. Total Bioenergy Potential in Ethiopia. Estimating the amount of biomass (including animal manure, crop residue, MSW, and forest residues) that can be used to produce bioenergy is crucial for the long-term sustainability of the biomass supply. According to the estimated findings, Ethiopia has a sizable residue biomass potential for bioenergy production, which could significantly improve modern energy access while reducing the use of biomass in conventional methods. Table 5 provides a summary of the bioenergy potential of the sources examined in this study.

From all sources potentially harvested residues across the country, a total of 2954.76 PJ·y^{-1} technical bioenergy and 819.7 TWh of electricity can be recovered, which is approximately 58 and 89 times Ethiopia's total electric production and consumption estimated in 2020 at 14.15 and 9.2 TWh [40], respectively, as shown in Figure 1. While the estimated total country's primary energy is roughly eight times the total country's bioenergy from all sources (105.8 TWh in 2020). The findings reveal that forest residues alone account for approximately 459 TWh·y^{-1}, 56% of the total potential. The traditional method of obtaining biomass provides above 80% of the country's energy. As much as 1655 PJ per year of the total 2954.76 PJ per year of potentially recoverable bioenergy has come from forest residues or about 56% of the total. Crop and animal residues have a respective bioenergy potential of 836 PJ·y^{-1} and 454 PJ·y^{-1}, with the remaining 9.8 PJ·y^{-1} potential coming from MSW from the country's major cities.

According to the study's results, it can be concluded that Ethiopia's residue biomass has the potential to be used as a replacement energy source to supplement conventional power sources. Approximately 55 M tons of biomass are consumed in conventional ways by the vast majority (above 80%) of rural Ethiopians [7]. They are hard to connect to the grid, and they do not have modern energy access. The only option, therefore, is to make modern, decentralized technologies available to rural communities. A comprehensive study on the supply of feedstock for the generation of bioenergy, food security, and value chains for bioenergy is required. It is important to exactly determine which feedstock, where, and how much of each type of bioenergy can be harvested. The competing demands for food, bioenergy production, and other necessities must be appropriately assessed. A thorough assessment of the competing demands for food, bioenergy production, and other needs is necessary. The costs and advantages of the relevant technology should be carefully considered. Therefore, to fully realize the potential of biomass as an energy source, this study recommends conducting integrated development research, identifying suitable bioenergy feedstock and value chains, and establishing a bioenergy database. While promoting and encouraging energy conservation and making sure that energy production is environmentally friendly and sustainable, the country needs to adequately support the private sector in key energy-consuming industries such as transportation, industry, and others [34]. In addition, it is important to promote the use of modern fuels, improve the efficiency of using biomass fuel, address domestic energy issues by promoting agroforestry, and incorporate environmental sustainability into energy supply and production systems [69].

4. Conclusion

This study examines the possibility of bioenergy production from residual biomass sources in Ethiopia. Using the main biomass production sources, Ethiopia has a total recoverable bioenergy potential of about 2954.76 $PJ \cdot y^{-1}$. The estimation reveals that the proportion of bioenergy potential from forest residue, crop residue, livestock waste, and MSW is about 56.01%, 28.29%, 15.36%, and 0.33%, respectively. This is in line with the 2013 Bioenergy Strategy Report and other similar previous studies in the country, which place crop residues as the second highest source of residue biomass after forest residues. If properly managed, municipal solid waste can make a significant contribution to the bioenergy industry. Energy poverty can likely be reduced and, ultimately, eradicated with the aid of small-scale decentralized bioenergy generation in a number of regional state areas. The issue of reliance on the grid for electricity will also be addressed by using this energy at various levels in the various regions of the country. The sustainability of bioenergy generation and utilization within the country will be ensured by the integration of various sectors, including academic institutions, research and development, the forestry and energy sectors, and the Ethiopian Environmental Protection Agency, as well as by encouraging various private stakeholders. Bioenergy production needs to be established in order to lower energy poverty, greenhouse gas emissions, and overall socioeconomic problems. The developed baseline for assessing biomass residues can also be used to create a comparable baseline and calculate the potential for producing bioenergy from locally available biomass resources in other parts of the country and abroad. It also establishes a platform for future research directions and studies into the social, economic, environmental, and technical aspects that might affect the realization of this bioenergy potential.

Data Availability

The data used in producing this article are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

Authors' Contributions

AT conceived, designed, and performed the experiments, analyzed and interpreted the data, contributed materials, analysis tools, or data; and wrote the paper.

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