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Article

Linking Energy- and Land-Use Systems: Energy Potentials and Environmental Risks of Using Agricultural Residues in Tanzania

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Abstract: This paper attempts to assess whether renewable energy self-sufficiency can be achieved in the crop production and processing sector in Tanzania and if this could be accomplished in an environmentally sustainable manner. In order to answer these questions the theoretical energy potential of process residues from commercially produced agricultural crops in Tanzania is evaluated. Furthermore, a set of sustainability indicators with focus on environmental criteria is applied to identify risks and opportunities of using these residues for energy generation. In particular, the positive and negative effects on the land-use-system (soil fertility, water use and quality, biodiversity, *etc.*) are evaluated. The results show that energy generation with certain agricultural process residues could not only improve and secure the energy supply but could also improve the sustainability of current land-use practices.

Keywords: agricultural residues; process residues; energy potentials; environmental sustainability; Tanzania

1. Introduction

Modern bioenergy applications are regarded as a promising option for decentralized energy generation in the rural areas of Sub-Saharan Africa, especially because large parts of the region have a high potential of producing biomass [1–3]. Arable land that is needed to grow biomass however is becoming a scare resource, not only because of the growing global demand for bioenergy from food and energy crops, but also due to factors like population growth, changing consumer habits, stagnating agricultural yields, soil degradation as well as climate change. This limited availability of agricultural land causes increasing competition between different forms of land use in parts of Sub-Saharan Africa as well as worldwide. As a result food security in developing countries is put at risk. In addition direct and indirect land-use changes are caused by the expansion of farmland and the shift to none-food crops. These land-use changes are responsible for significant amounts of the greenhouse gas emissions and can harmfully affect the water cycle, the nutrient cycle, biological diversity and soil quality [4]. Due to these challenges, bioenergy strategies have to be carefully chosen, especially in low-income and food-deficit countries like Tanzania.

Bioenergy pathways that are not directly linked to land-use competition and land-use changes are those which utilize biogenic wastes and agricultural residues. Even though other interconnections between land-use-systems and energy systems based on agricultural residues exist. Yet wastes and residues, such as those from agricultural processing, represent a still largely untapped energy potential worldwide [5]. This is expected to be particularly true in a country like Tanzania, where agriculture is the dominating economic sector, accounting for approximately 25% of GDP, providing 85% of exports, and employing 80% of the workforce [6]. Accordingly, bioelectricity from agricultural residues, such as bagasse, is currently only generated in small quantities. The country's primary energy requirement is met through traditional biomass fuels like firewood or charcoal (90% of consumption), which is the typical situation of countries in Sub-Saharan Africa. Electricity is mainly generated from hydropower (561 MW capacity) and thermal-based generation with diesel and natural gas (658 MW capacity) [7]. Overall electricity accounts for only 2% of the energy consumption in Tanzania, [7]; but the demand for electricity is expected to triple until 2020. Drivers for this development are continuing growth in the commercial, industrial, agricultural and residential sector, population growth, expanding electrification and increasing *per capita* electricity consumption. Because the latent demand already exceeds the electricity supply, continuing power shortages occur and new power rationings were announced in 2010. This situation threatens the overall economic growth as well as the competitiveness of Tanzania's vital agro-industrial sector. Companies and farms have either to rely on expensive backup systems like diesel generators or to completely suspend their business activities during load sheddings. The World Bank estimates that the average cost of electricity shortcomings in Africa are equivalent to 2.1% of the gross domestic product (GDP) [8]. Therewith, the question of how to stabilize, secure and increase the power supply is a critical one for Tanzania's agro-industrial sector as well as for economic and social development of the surrounding rural areas.

Utilizing the energy potential of available agricultural residues could be a strategy for farms and companies in the agricultural sector to cope with the enduring power supply problems. For some parts of the sector it might even be possible to become energy self-sufficient, particularly as the most considerable amounts of agricultural residues are produced on private estates and in intensive commercial smallholders farming systems, which produce one-fifth of the agriculture production in Tanzania [9]. The most promising residue type for energy generation are thereby residues accumulated during crop processing, because of their large and localized availability at the processing sites. Utilizing residues which currently remain on the fields after the harvest will require additional logistic structures. Therefore, the focus of the early stage of electricity generation from agricultural residues should be the utilization of already available process residues.

2. Research Objectives

As already mentioned, this approach entails far fewer risks of land-use competition and does not jeopardize food security. Nevertheless, energy systems based on agricultural residues are linked to land-use systems where these agricultural residues are produced. These links can have positive as well as negative effects on the land-use systems. Therefore, it is very important to examine how these bioenergy systems can be/are linked to the concept of sustainable land use and to identify such risks and opportunities (the FAO's definition of sustainable land use is used here: 'Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: (1) maintain or enhance production/services (Productivity); (2) reduce the level of production risk (Security); (3) protect the potential of natural resources and prevent degradation of soil and water quality (Protection); (4) be economically viable (Viability); (5) and socially acceptable (Acceptability)' [10]). Respectively, the research objectives of this study are to conduct a detailed country level and crop specific assessment to understand the current stage and practical prospects for energy generation from agricultural residues in Tanzania. In particular, the theoretical potential of cogenerating energy with residues from Tanzania's commercial agricultural crop sector will be assessed with the following detailed objectives: (i) to estimate the theoretical available amount of agricultural crop residues; (ii) to evaluate the availability and technical realizable energy potential of the residues; (iii) to assess ecological effects of using these residues for energy generation.

3. Results and Discussion

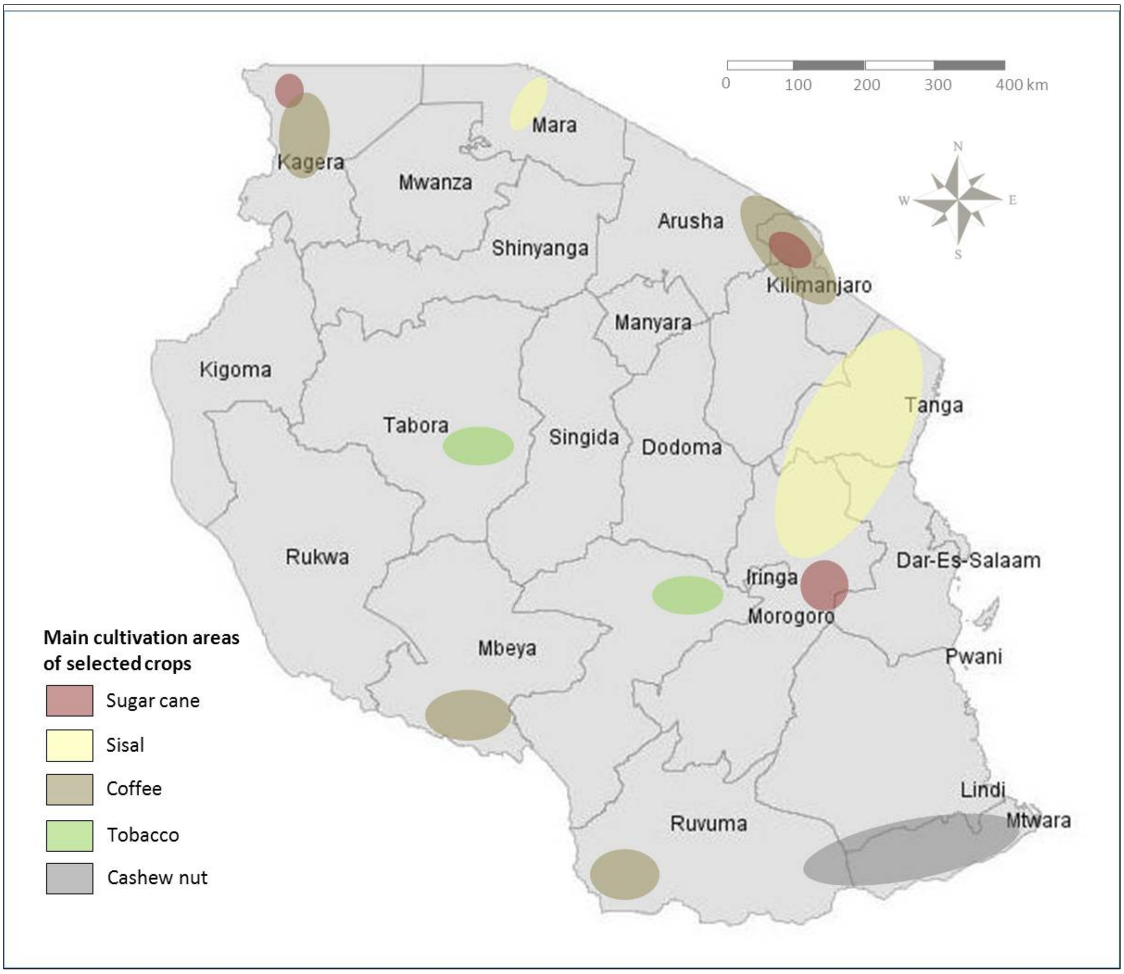
3.1. Assessment of the Residue and Energy Potentials

The major commercially produced agricultural crops in Tanzania are sugar, cotton, tea, cashew nut, tobacco, coffee and sisal. Significant amounts of residues from these crops have so far only been utilized for the cogeneration of electricity in the sugar sector. Besides that only a small amount of sisal residues has been used as substrate in a pilot biogas plant to generate electricity since 2008. Hence, the following section aims at quantifying and evaluating the amount of residues produced from each commercial crop, before estimating the theoretical energy potential of these residues. The theoretical energy potential will be derived from the physical supply of biomass sources and represents the theoretical upper limit of the available energy supply [4].

3.1.1. The Commercial Agricultural Crop Sector in Tanzania

The agricultural sector is dominated by subsistence farming and rain-fed crop production [9]. Accordingly, many of the important commercial crops are grown on small-scale farms, often in out-grower schemes (out-grower schemes can be defined as contract faming with binding arrangements through which companies ensures their supply of agricultural products by individual or groups of farmers [11]). Crops like sisal, sugar cane, tea, coffee and tobacco however, belong to the few crop varieties that are also commonly grown on large-scale farms. While agriculture also mainly depends on rainfall and only about 3% of the agricultural land is irrigated, cash crops like sugar cane, cashew nut and coffee are cultivated with up to 24% of the planted area under irrigation [12]. Harvesting on the other hand is predominantly done manually, regardless of the size of the farm and the cultivation method. Only a very small number of commercial farms rely partly on machinery for harvesting. The schematic Figure 1 gives us an overview where the main cultivation areas of sugar cane, sisal, cashew nut, coffee and tobacco are located within Tanzania.

Figure 1. Simplified overview of the main cultivation areas of selected crops in Tanzania.



As shown in Table 1, sugar cane is by production quantity the most important commercial crop in Tanzania. In opposite to other major commercial crops, nearly 100% of the sugar produced in Tanzania is also sold and used within the country. Coffee on the contrary is mainly exported and accounts for about 20% of Tanzania's foreign exchange earnings [13]. Therewith, it has been the dominating cash crop in the country's agriculture-based economy since its introduction 100 years ago. The main cultivation areas of the coffee plant can be found in Arusha, Iringa, Kilimanjaro and Mbeya [12].

The most important export crop after coffee is cotton, which is mainly cultivated in the lake zone [14]. But the cultivated area has declined by about 10% in 2010 compared to the previous season. The reason for this was the anticipated decline in cotton prices due to the international economic and financial crises [15]. Similarly affected by the global economic downturn was the sisal sector, where the production dropped by about one-third from 2008 to 2009 [16]. Sisal fiber, which is mainly cultivated on large-scale farms in the regions of Tanga, Morogoro Kilimanjaro and Mara [16], is traditionally used to produce ropes, carpets and clothing. Recently the fibers have also been processed in the automotive sector and for specialist paper manufacturing, leading to a worldwide upward trend in fiber demand. However, this worldwide trend has so far shown no effect on the sisal production in Tanzania.

The tobacco production, which has continuously increased over the last decade, was unaffected by the economic instabilities. Tobacco is one of the major cash crops in Tanzania and is grown on large-scale as well as small-scale farms mainly in the regions of Tabora and Iringa. Another important export product of Tanzania is tea, which is cultivated in the southern highlands as well as in the northeast and northwest of the country. Half of the planted area is owned by large private tea estates while the other half is cultivated by out-growers and smallholders [17]. In comparison, the cashew nut production is dominated by small-scale farmers, who produced 99.5% of the harvest in 2003. The few large scale cashew nut farms that exist can be found in the dry coastal areas of Tanzania [12].

3.1.2. Types of Residues and Potential Availability in the Commercial Crop Sector

These commercial crops grown in Tanzania generate various types and amounts of residues depending on the plant structure, seasonal availability, harvesting methods, irrigation practices, soil quality and other factors. So far, the management of these residues varies from crop to crop and from farm to farm. Traditionally, most of the agricultural crop residues are burnt, left on the fields or on the farms aiming to facilitate the harvesting process, as pest control measures or simply because there is no other possibility to dispose the residues. Due to the worsening wood fuel scarcity in Tanzania, an increasing amount of residues is also directly used as cooking fuel, but this mainly applies for residues from grain and fruit crops. Moreover, agricultural residues are a poor fuel for direct combustion because of the relatively low energy content per volume; therefore, people prefer to use other energy sources if such are available and affordable to them.

To estimate the potential availability of agricultural residues for modern energy generation the residue-to-product ratio (RPR) is applied [18]. This method has been widely used and is based on the defined relationship between crop yield and residues left after the extracting of the product [19]. Although this approach has its limitations (e.g., it does not include future developments and investments in the agricultural sector), it is suitable to estimate the current country-specific energy potential of residues. The general equation for estimating the agricultural residual biomass is as follows:

$$R = Cp * RPR \tag{1}$$

where (R) is the total available agricultural residual biomass in tonnes per year, (Cp) the amount of crop production in tonnes per year and (RPR) the residue-to-product ratio in tonnes of residues per tonnes of product. The theoretical available types and amounts of process and field residues found in the commercial crop sector in Tanzania are shown in Table 1, based on average annual production data from 2000–2009.

Table 1. Types, amounts and availability of residues from selected crops in Tanzania based on average annual crop production data from 2000–2009.

Crop	Annual Crop Production [t] [1]	Process Residues	Field Residues	RPR [2]	Annual Residue Production [t]	Harvesting season [month/ year]	Availability of residues
Sugar Cane	2,046,500	Bagasse		0.30	613,950	8	Nearly 100% is already utilized as boiler fuel to generate electricity for the sugar mills & plantations
			Cane tops & leaves	0.29	593,485	8	None—Nearly 100% are burnt in-field to facilitate harvesting
Coffee	49,228	Husks		0.25	12,307	6	Available at the processing plants
			Cherry pulp & skin	1.40	68,919	6	Mostly wet coffee processing: pulp and outer skins are removed in decentralized locations during harvest & not centrally available for energy generation
Cotton	232,959		Stalks	2.20	512,510	3–4	Stalks are left or burnt in the field after picking the cotton, stalks are also used as fuel for fire-stoves by poor families
Cashew nut	92,906	Shells		2.10	195,103	4	Only about 17% are processed (shelled) in Tanzania, the rest is exported as raw nut so that shells are not available
Tea	29,060		Stalks	1.20	34,872	12	Are left on the field as fertilizer
Tobacco	39,613	Stems		0.95	37,632	4–5	
			Stalks	2.00	79,226		
Sisal	25,950	Sisal pulp		24.00	622,800	12	All available at the processing plants, currently not utilized due to liquid nature, (besides small amount in a biogas pilot plant); in the future possible use as fodder (testing stage)
			Sisal ball	4.70	121,965		Currently burnt or broken down & plowed under

[1] [20]; [2] Residue-to-product ratio based on [18,21–26].

As Table 1 indicates, not all of these residues are available for energy generation because they are already utilized by competing applications. These applications can be summarized as ‘the 6 F’s’: Fuel, Fodder, Fertilizer, Fiber, Feedstock and Further uses [18,27]. Field residues for example play an important role in returning nutrients to the soil, keeping the moisture content in the soil up and protecting the farm land from erosion. Clearly, removing these residues could have negative effects on farm land and production yields. Therefore field residues will not be considered in this study as feedstock for energy generation (Although field residues will not be considered in this country level potential assessment, field residues might be available for energy generation in some regions and for some projects, depending on the local conditions.). The residue data in Table 1 also shows that only small quantities of the most promising residue fraction, the process residues, are available. In the case of bagasse most of the energy potential is already utilized, while more than 80% of cashew nutshells are exported with the main product, the cashew kernel.

3.1.3. Theoretical Energy Potential of Selected Process Residues

Nearly all biomass can be converted into energy; this correspondingly applies to crop residues. The types of residues available for energy generation in the commercial crop sector in Tanzania are bagasse, coffee husks, cashew nut shells, tobacco stems and sisal pulp. The energetically available share of these residues is determined by the described non-energy uses, while the energy content of residues is influenced by the plant structure and the moisture content of the residue. Taking these different parameters into account, the heating value per tonne of dry matter was calculated (Table 2). Although this is an optimistic estimation because losses are to be expected during collection and transportation, this upper bound shows that all residue types contain a noteworthy energy potential. The combined potential of 6,053 TJ, is equivalent to 1,680 Gigawatt hours (GWh). This estimated maximum potential is equivalent to over 37% of the country's electricity generation of 4,553 GWh in 2008 [28]. Of course this theoretical energy potential which is derived from the physical supply of biomass sources and represents the theoretical upper limit [4], cannot be fully realized with the current technical possibilities. Furthermore the energy potential of bagasse which represents two thirds of the overall potential is already utilized. Nevertheless, utilizing the unused energy potentials could contribute to meeting the growing electricity demand and offers an opportunity for decentralized electricity production in Tanzania.

Table 2. Average annual energy potential of selected agricultural crop residues in Tanzania.

Crop	Residue type	Estimated availability factor	Residue [wet t]	Moisture content [1] [%]	Residue [dry t]	Residue [2] energy value [LHV GJ/t]	Residue energy potential [TJ/yr]
Sugar cane	Bagasse	1	613,950	48–49	316,184	12.5	3,952
Coffee	Husks	1	12,307	13	10,707	12.2	131
Cashew nut	Shell	0.17	33,167	6,5	31,012	14.9	462
Tobacco	Stems	unknown	37,632	9	34,245	12.6	431
Sisal	Pulp	1	622,800	88–94	74,736	14.4	1,076
Total			1,319,857		466,884		6,053

[1,2] Based on [18,21–24,29–31].

Converting crop residues into energy can be done using various biochemical and thermochemical energy technologies. The conversion pathways considered in this analysis (Table 3) have been chosen based on the following criteria: (a) currently used and proved technologies; (b) promising new technologies or new fields of technology applications in the African context (pilot stage). The numerous technologies using gasification and pyrolysis that are currently in the demonstration stage are not considered here as these technologies are so far concentrated in Europe, USA, Japan and India [32].

Table 3. Overview of energy conversion pathways and possible plant size for selected residues.

Crop	Residue type	No. of medium to large scale processing sites	Conversion pathways	Expected efficiency	Product	Average energy plant size [MW]
Sugar cane	Bagasse	6	Combustion	15–25%	Steam, electricity, heat	8–9
Coffee	Husks	23	Combustion Briquetting	15–25%	Steam, electricity, heat Solid fuel	0.5–1
Cashew nut	Husks	14	Combustion	15–25%	Steam, electricity, heat	0,1–1
Tobacco	Stems	unknown	Anaerobic digestion Briquetting	25–36%	Biogas, electricity, heat Solid fuel	___
Sisal	Pulp	35	Anaerobic digestion	25–36%	Biogas, electricity, heat	0.1–1

The most dominating residues by far is sisal pulp, but the liquid nature of the residues has so far been regarded as restriction for any uses. Nevertheless, laboratory experiments [33–35] and the first pilot plant, operating since 2008, demonstrated that sisal waste can be transformed into electricity by utilizing biogas through anaerobic digestion. With 35 operating sisal processing sites of various sizes, the identified energy potential is suitable for small-scale decentralized power generation with capacities ranging from 100 kW up to 1 MW. Bagasse on the other hand, which represents the second largest energy potential (Table 2), is already utilized as energy feedstock to cogenerate steam and electricity at four of the five processing sites in the country. But traditionally sugar factories only produce steam and electricity to meet their own energy needs. So far only one estate has modernized its power plant, increasing its generation capacity to 17 MW. Most of the other sugar factories could potentially also produce surplus electricity, if they would increase efficiency and/or their generation capacities.

Coffee husks are generally not used as modern fuel source in Tanzania. However, they could be used for the production of fuel briquettes or fed directly into the combustion flame to replace coal or other fossil fuels in electricity production. Until now, there has only been one attempt to produce briquettes from coffee-husks by the Tanzanian Coffee Board. But as many briquetting facilities in Africa, it has been unsuccessful due to technical difficulties. The other two biomass residue streams that are taken into account for this analysis are cashew nut shells and tobacco stems. Cashew nut shells are available at 4 large-scale and about 10 medium-scale processing plants. The shells are currently not utilized as energy source in the cashew nut industry itself, but recently a cement factory in Tanga has started to substitute fossil fuel with cashew nut shells to meet their heat energy needs.

With regard to the possibilities of reaching energy self-sufficiency in the agro-industrial crop production in Tanzania it can be stated that the sugar cane irrigation and processing is close to being energy self-sufficient. Furthermore sufficient energy potential exists in sisal and cashew nut processing. With energy generation in the sugar sector becoming more efficient, even surplus energy could be generated and sold. The same could be possible in sisal and cashew nut processing sector, as even with the losses during conversion, the energy potential exceeds the energy needed to process the crops. In the coffee sector the energy potential is not sufficient for the energy intensive coffee processing but significant amounts of fossil fuel inputs could be replaced by utilizing the residues.

3.2. Assessing Environmental Risks and Opportunities

Compared to other biofuels the use of agricultural residues for energy purposes has the advantage of avoiding land-use competition and greenhouse gas emissions from land-use changes. But other effects on the land-use system remain of concern [4,5]. Therefore, factors that define how and where the energy potential can be utilized in an environmentally sustainable manner need to be assessed. The evaluation of environmental risks and opportunities is based on a selection of sustainability criteria developed by the Roundtable on Sustainable Biofuels (RSB). Altogether, the RSB defines twelve principles that focus on social and environmental sustainability [36]. The following four aspects have been identified as primary for the evaluation of the environmental sustainability utilizing agricultural residues in Tanzania and were applied in this study: greenhouse gas (GHG) emissions, water use and quality, biodiversity and soil health. With regards to the lifecycle of the residual plant materials, the effects and interaction with the current cultivation structures are integrated in the environmentally sustainability assessment.

3.2.1. Greenhouse Gas Emissions

If waste disposal is understood as the management of waste for the duration of its biological and chemical activity to prevent negative effects on the environment, most unused agricultural residues are currently not properly disposed in Tanzania. The decomposition of residues left in the open air leads to the formation of methane (CH_4) which is then released into the atmosphere. Methane is about 25 times more potent as a GHG than carbon dioxide (CO_2) and contributes heavily to atmospheric warming and its associated negative effects on the environment [37]. By utilizing residues for energy generation these emissions can be avoided or at least be reduced. This would significantly reduce lifecycle GHG emissions and contributing to climate change mitigation. The combustion of solid residues in power plants or as briquettes represents furthermore the best way of eliminating these residues, as this process leads to significant reduction in volume [38].

3.2.2. Water Use and Water Quality

Agricultural based economies like Tanzania require large amounts of water for irrigation and crop processing. Up to 90% of the total water withdrawals in Tanzania are accounted for by the agriculture sector, of which the largest amount is used for irrigation purposes [39]. In addition to the irrigation the processing of agricultural crops can also be very water intensive. Particularly in Tanzania, where water is a scare resource, water use is an important factor that needs to be considered if the biomass production aims at being sustainable [36]. Table 4 shows the intensity of water use for the identified commercial crops with a high residue generation potential.

The use of the process residues for energy purposes does not require large amounts of additional water inputs. Only conversion pathways like biogas recovery would need considerable amounts of water, but in the case of sisal the waste has already a high moisture content and additional water from the processing can be utilized. Solely for the relatively dry tobacco stems water would have to be added to produce biogas. Tobacco processing itself is further indirectly associated with high water requirements. As huge amounts of fire wood for the curing process are needed and eucalyptus trees are often cultivated to meet this fire wood demand. The resulting problem for the water balance is that non-indigenous species like the eucalyptus tree draw a lot of underground water reducing the groundwater pool and water availability over time.

Another important factor is water quality; biomass production for energy generation should not lead to contamination of water sources [36]. Crop cultivation utilizing chemical fertilizers and pesticides can have negative effects on the regional water quality and lead to water pollution. This has already been the case in the sugar cane, coffee and tobacco sector with their high fertilizer and pesticides inputs. The energy conversion pathways for bagasse, coffee husk, cashew nut shells and tobacco stems on the other hand have no direct negative or positive effects on the water quality. The utilization of sisal residues in contrast can significantly reduce ground and surface water pollution [40]. Because water from sisal processing is currently simply drawn off to nearby water sources, being the main origin of water pollution in regions with high sisal production. Utilizing and treating sisal pulp and wastewater during the energy generation process therewith directly benefits the environment and helps to fulfill the sustainability requirement [26].

3.2.3. Biodiversity

The standards of the RSB require that biofuel operations shall avoid negative impacts on biodiversity, ecosystems, and other conservation values if they aim at being sustainable [36]. As described before, removing residues from the fields can have various effects on the ecosystem but utilizing process residues has no direct effects on biodiversity. Yet when considering the lifecycle of the residual plant materials, the cultivation of the crops itself can significantly distress biodiversity. The degree of biodiversity in agricultural ecosystems depends on the diversity of vegetation within and around the agro-ecosystem, permanence of crops and intensity of management [41]. Respectively, Table 4 displays selected indicators that influence the biodiversity in the considered agricultural ecosystems.

The dominating form of cultivation for sugar cane, sisal and coffee are monocultures, which are known to significantly reduce biodiversity by replacing nature's diversity with a small number of cultivated plants [42]. Most common shortcomings arising from monoculture cultivations include displacement of natural vegetation, nutrient losses and intensive use of fertilizer and pesticides. As Table 4 shows, this is true for all three crops, with the exception that sisal is grown rather extensively without the use of chemical fertilizer or pesticides. Nonetheless, sisal is the most dominating crop in its main cultivation areas; dominating the scenery in the regions of Tanga and Morogoro. Whereas tobacco cultivations are not as prevailing, fertilizer use is the highest among all crops in Tanzania. The processing of tobacco has further severe effects on the ecosystem, as it requires high amounts of firewood. Tobacco processing therewith contributes strongly to deforestation in the tobacco growing regions. Cashew nut trees again are perennial crops that are not primarily grown in monocultures and do not require intensive farming methods (Table 4). Thus, different crops have different effects on the biodiversity, but especially the monoculture cultivations significantly reduce biodiversity in core growing regions of Tanzania. Risks of additional biodiversity loss for all crops exist, if expansion and intensification are undertaken to generate additional residues for energy purposes. However, the use of currently generated residues does not implicate further biodiversity losses.

Table 4. Selected indicators that influence environmental sustainability in the context of energy generation with process residues in Tanzania.

Indicator	Sisal	Sugar cane	Coffee	Cashew nut	Tobacco
Water use					
Irrigation	None	✔ (24%)	✔ (15%)	✔ (32%)	✔
Water use processing	High	Low	High	Low	Low
Biodiversity & soil health					
Agricultural area per crop [ha]	188,131	45,000	265,000	288,520	57,438
Average area per estate/farm (small & large scale) [ha]	Estate: 34,842	Estate: 90,000	Small scale: 0.42 Large scale: 71	Small scale: 1.4 Large scale: 97	Small scale: unknown Large scale: 256
Structure	10% smallholder 90% large scale	55% smallholder 45% large scale	89% smallholder 11% estates	99% smallholder 1% large scale	90% smallholder 10% large scale
Number of plants per ha	3,000–4,000	-----	ca. 1,100	-----	-----
Cultivated area [%]	Total: 3.7 (*Regions:* Tanga 67; Morogoro 23; Kilimanjaro 6; Mara 4)[2]	Total: 1 (*Regions*: Morogoro 3; Kilimanjaro 2)	Total: 5.3 (*Regions*: Arusha 11, Kilimanjaro 20; Mbeya 10, Ruvuma 9, Kagera 10)	Total: 5.8 (*Regions*: Lindi 12; Mtwara 42, Ruvuma 5)	Total: 1.2 (*Regions*: Tabora 7, Iringa 8)
Dominance of non-domesticated species to domesticated species	High in Tanga and Morogoro	-----	High in Kilimanjaro	High in Mtwara	-----
Cultivation mainly in monocultures	✔	✔	✔	no—mostly intercropping	monocultures not dominating
Use of agricultural pesticides	None	✔ (High)	✔ (Very high)	✔	✔ (High)
Use of inorganic fertilizers	None	✔ (High)	✔ (High)	✔ (Very low)	✔ (Very high)

Sources: Field research, [12,15,16,20,43–46].

3.2.4. Soil Health

Agricultural residues contain nutrients and maintain soil carbon content and fertility. They also provide protection against erosion and can contribute to soil biodiversity [5,32]. Therefore, environmentally sustainable biomass operations should implement practices that seek to maintain soil health to and/or reverse soil degradation [36]. For this reason field residues were not considered as energy source in this study, as they play an important role in maintaining the nutrient cycle.

As mentioned before, some crops are mainly grown on monoculture plantations. These plantations have often existed for decades, continuously cultivating the same crop, and thus leading to deficits in the nutrient balance as well as in the overall soil nutrient content. This is particularly the case for sugar cane and sisal plantations where almost no residues are left on the field to return nutrients to the soil. Fertilizers are used in the sugar, coffee and tobacco sector to compensate for these nutrient losses. In the sisal sector where no fertilizer is used the nutrient loss result in decreasing yields per hectare.

While the cultivation methods can lead to an impoverishment of the soil, converting plant residues to energy can contribute to improve the soil health [47]. This is the case if residues from the energy conversion process are utilized as fertilizer. Using residues to generate biogas could therewith improve the nutrient regime, since the digestate from biogas generation can be used as organic fertilizer. The same applies to ash and sludge from the combustion process which can be brought back onto the field as fertilizer. This is already practiced on certain sugar estates in Tanzania, while for the digestate from the sisal biogas plant logistics constitute an obstacle for its use as fertilizer. Consequently, the utilization of process residues for energy generation can in theory contribute to improving the soil conditions or at least act contrary to the nutrient losses.

In the case of cashew nuts shells the utilization of the shells would have further positive effects for the environment, because the shells contain the poisonous “cashew nut shell liquid”. This toxic liquid can cause serious irritations if it comes in contact with the skin [48]. Leaking out from the piles of unused cashew nut shells it currently pollutes the soil and nearby water bodies.

4. Conclusions

The scope of this study was to conduct an assessment of the energy potential of agricultural residues from the commercial crop sector in Tanzania and to emphasize the multiple factors that influence availability and environmental sustainability. In particular, the theoretical, residue potentials and the available energy potentials have been differentiated. It has been found that even if initially only the available processing residues are used, sufficient amounts of residues exist in the sugar, sisal and cashew nut sector for crop processing to become energy self-sufficient. Further potentials exists in the coffee sector, while due to missing data no final result could be presented for the tobacco sector.

Utilizing the potentials implies environmental risks as well as opportunities. If the energy generation with process residues aims to be environmentally sustainable, these factors need to be taken into consideration. Assessments of bioenergy potentials often focus on the environmental factors biodiversity and climate while soil and water aspects are often omitted [49].

With respect to these observations this study tries to extend the scope to the effects on soil and water. The evaluation of the criteria showed that for all crops environmental risks exist in the current growing and processing practices. However, utilizing the process residues for energy purposes entails numerous opportunities and could in some cases lead to an improvement of the current situation (Table 5).

Table 5. Overview of effects on environmental sustainability in Tanzania.

	Sustainability criteria	Growing and processing	Using residues for energy generation
Environmental	Greenhouse gas emissions	-	++
	Water use & water quality	--	+
	Biodiversity	--	
	Soil health	--	+

++ very positive; + positive; +/− can have positive or negative effects depending on implementation; - negative; -- very negative.

There are noteworthy limitations of this study that need to be acknowledged and addressed. First, the assessment of the country specific potential cannot reflect local conditions, meaning that a revision of the regional and local potential could either result in a higher or reduced amount of residues and energy potentials available. Nevertheless, these results can serve as input for site specific sustainability assessments of locally available potential and help create awareness among potential investors and policy makers about the viability of residues as a source for electricity generation. The next steps would have to be the assessment of socio-economic factors that need to be taken into account if the production and use of bioenergy should meet the requirements for sustainable development [4]. These aspects need to be especially careful assessed in developing countries like Tanzania, where the agricultural sector plays a key role for economic and social progress. Although decentralized energy generation with agricultural residues has potential to provide the rural poor with multiple benefits, no guarantee exists that activities help to satisfy local development needs.

Conflict of Interest

The author declares no conflict of interest.

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