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Review

Socio-Economic and Environmental Implications of Bioenergy Crop Cultivation on Marginal African Drylands and Key Principles for a Sustainable Development

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Abstract: Africa has been a hotspot for the development of food and bioenergy crop cultivation since the 2000s, leading to systematic challenges towards its ability to become a bioeconomy. To reduce land-use conflicts with food crop cultivation, marginal African drylands (MADs) are proposed for sustainable bioenergy cropping systems (BCSs). This study reviews the foremost socio-economic and environmental challenges for BCSs on MADs, and the development of key principles for minimizing adverse outcomes towards a sustainable bioeconomy. Socio-economic prosperity in Africa depends on several systematic solutions, and BCSs that are based on perennial bioenergy crops are promising strategies as they provide a renewable and sustainable energy source for rural areas. However, critical multidimensional challenges such as poverty, food security, gender equality, access to energy, and environmental impact must also be considered to ensure long-term sustainability. This review argues for more transparent land sales/usage (considering the agricultural work of women) and more perennial bioenergy crops. In this context, key principles were derived for a people-centered bottom-up approach that is considered fundamental to ensure the sustainable development of BCSs on MADs in the future.

Keywords: affordable and clean energy; biodiversity; clean water; climate action; energy security; gender; marginal land; marginal agricultural land; perennial crops; rural development

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Citation: Varela Pérez, P.; Greiner, B.E.; von Cossel, M. Socio-Economic and Environmental Implications of Bioenergy Crop Cultivation on Marginal African Drylands and Key Principles for a Sustainable Development. *Earth* **2022**, *3*, 652–682. https://doi.org/10.3390/earth3020038

Academic Editors: Samuel Asumadu-Sarkodie and Helder Fraga

Received: 11 April 2022
Accepted: 25 May 2022
Published: 28 May 2022

1. Introduction

Bioenergy crops represent a promising sustainable alternative for finite fossil-based resources, as well as a more reliable, predictable, and independent renewable source compared to solar and wind energy which can only be produced as long as the climate conditions allow it [1,2]. Likewise, due to their natural unpredictable energy flow fluctuations, it becomes a challenge to balance demand and supply, which leads to negative economic externalities [1,2]. However, the cultivation of bioenergy crops in so-called bioenergy cropping systems (BCSs), especially those with a perennial life cycle, can provide valuable ecosystem services, such as erosion mitigation, carbon sequestration and biodiversity [3]. A well-developed ecosystem service performance represents a substantial competitive advantage to overcome diverse environmental challenges [4]. Furthermore, despite the aforementioned positive contributions, there are representative controversial discourses concerning land use for food vs. fuel production which have been an important matter of discussion on global agendas [5]. Food and fuel collide due to land and water scarcity caused by anthropogenic changes, and social megatrends, such as population growth [6,7]. By 2030 the world's population will increase by 33% (6–8 billion), leading to an increased demand of 50% for food, 30% for water, and 50% for energy [6]. By 2050 the scenario is even more alarming since feed production is forecasted to increase 70% globally and 100%

in developing countries [7]. Hence, marginal lands in the last 20 years, including drylands, have won global interest as a potential source of land for the cultivation of crops, including bioenergy crops [5,8–10]. A concrete definition of marginal land is complex to provide since the term is relative [11]. Hence, a broad definition was used for this review, following which marginal drylands are lands affected by low precipitation; drought; land degradation, such as wind and water erosion; vegetation degradation; and salinization [12,13]. This results ultimately in desertification, which consist of the decline of ecosystem service performance, including the provision of biomass [12,13]. Drylands are the largest biome on our planet, corresponding to 41–45.4% of the global surface area. The major drylands are located in Asia and Africa, summing a total of ~31% of the global surface area of which the latter is most affected by desertification [12–14], (Figure 1). Their current state falls under the meaning of the term 'marginal land' that is considered for this review, *"Depending on time and place, marginal land may also refer to idle, under-utilized, barren, inaccessible, degraded, excess or abandoned lands, lands occupied by politically and economically marginalized populations, or land with characteristics that make a particular use unsustainable or inappropriate"* [10].

Figure 1. Drylands near Taung in the margins of the Kalahari Basin, South Africa (Image credit: B. Winkler).

Correspondingly, more than 2 billion people depend on drylands, indicating that they are home to one in three persons worldwide (90% live in developing countries) [12,15]. Global food security depends on dryland productivity since more than 45% of the world's cultivated systems are in this land system [15,16]; hence, drylands are the basis for ~60% of the world's food production [16]. Furthermore, drylands, due to their spatial magnitude, store ~46% of global carbon share, an ecosystem service that contributes significantly to climate change mitigation [17]. Nevertheless, these contributions are under risk as drylands are being severely affected, principally by climate change, unsustainable land use, and water scarcity, leading to land degradation (desert-like conditions). Globally, 10 to 20% of drylands are degraded [17].

In Africa, marginal drylands represent a potential hotspot for bioenergy crop production [18] and an opportunity to help overcome their main societal challenges, such as food insecurity, and poverty for an increasing population. Since technological and innovation advancements are crucial for economic growth and development, modern bioenergy system promise to contribute to achieving economic transformation, with potential societal benefits expanding to multiple sectors and extending beyond a more sustainable energy supply [19,20]. In the present review, the term "modern bioenergy" would be exchanged for "bioenergy".

Against this backdrop, the present study was aimed at: (i) the identification and assessment of the foremost socio-economic and environmental challenges from BCSs on marginal African drylands (MADs) based on the 17 Sustainable Development Goals (SDGs); (ii) the development of key principles that help to detect and minimize likely adverse outcomes.

2. Materials and Methods

A thorough literature review was conducted using Scopus (Elsevier B.V., Amserdam, The Netherlands) and Google Scholar (Google, Mountain View, CA, USA). Based on four basic keywords (Table 1), a total number of 17,509 documents was preselected of which 309 were from Scopus and 17,200 were from Google Scholar. Using the Boolean operators "AND" and "OR", these documents were then screened for refining keywords (Table 1) for the two categories "socio-economic" and "environmental".

Table 1. Overview of basic and refining keywords used for the literature search in this study.

Basic Keywords	Refining Keywords	
	Socio-Economic	Environmental
Africa	Agriculture	Agriculture
Bioenergy	Food security	Environment
Marginal	Hunger	Climate change
Drylands	Food vs. fuel	Biodiversity
	Gender equality	Water scarcity
	Energy access	Sanitation
	Energy poverty	Eutrophication
	Women in agriculture	Marine pollution
	Mini-grid system	Biodigester
	Poverty	Perennial crops
	Economic growth	CAM plants
	Human development	

In general, the selection of relevant studies did not follow a specific scheme because of the wide scope of this study. Instead, the screening of the literature was focused on: (i) most recent or highly cited publications; (ii) publications with a focus on African countries or on marginal drylands. However, the reference lists of the studies found were also considered for identifying additional relevant references.

3. Review Linked to the SDG Aspects

The principal socio-economic and environmental challenges of BCSs on MADs were identified using the Sustainable Development Goals [21] as a guideline and considering the interactions between MADs and the global level (Figure 2). Several global conditions such as markets, foreign investment, climate, and the biomes of the respective region were identified that should be considered in the development of sustainable BCS. In some cases, indirect influences of the global framework were also identified; for example, due to interactions between world markets and the behavior of foreign investment companies (or countries). Primarily, however, local environmental or societal conditions and expectations are crucial for the requirements of sustainable BCS on MADs. In the following (Sections 3.1 and 3.2), the results of the socio-economic review and the environmental review are presented and discussed in more detail. After that (Section 4), the key principles for the sustainable development of BCSs on MADs are discussed.

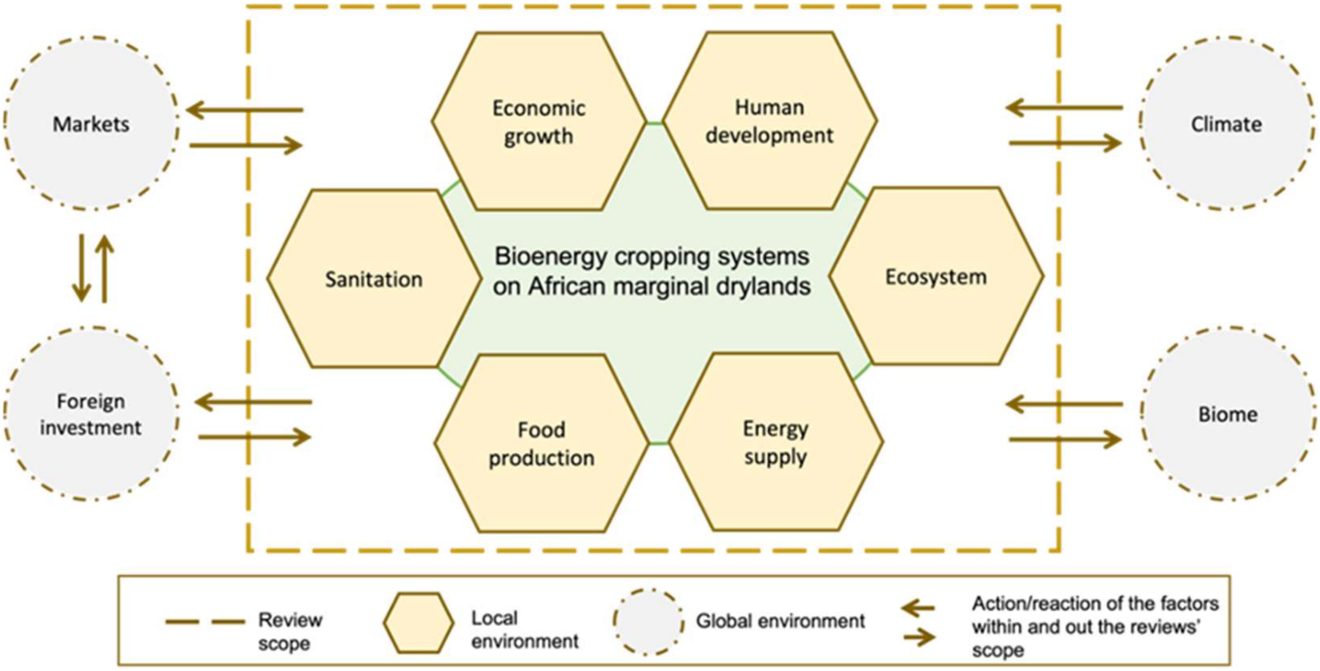

Figure 2. Overview of major factor categories, dimensional levels and interactions that address bioenergy cropping systems on marginal African drylands.

3.1. Socio-Economic Review

This section addresses the foremost socio-economic challenges that need to be considered before the implementation of BCSs on MADs. The section centralizes on the following societal issues and corresponding SDGs (Figure 3):

- Poverty (SDG 1—Poverty);
- Food security (SDG 2—Zero hunger);
- Land grabbing (SDG 16—Peace, justice and strong institutions);
- Gender equality (SDG 5—Gender equality);
- Clean and affordable energy access (SDG 7—Affordable and clean energy).

3.1.1. Poverty

Despite the economic and social welfare that Africa has accomplished over the last decades, poverty rates in most African countries are the highest in the world [22]. The share of people living in extreme poverty has substantially decreased from 54% in 1990 to 41% in 2015; however, more Africans are living in poverty today than in 1990 [8].

Of the world's 28 poorest countries, 27 are located in Sub-Saharan Africa (SSA), and all of them with poverty rates above 30%, highlighting: Nigeria, Congo Democratic Republic, Tanzania, Ethiopia, Madagascar [22]. Today, about 3:5 world's poor live in Africa, with 82% of them living in rural areas, whose incomes depend on agriculture and where the most affected group is women [23]. The forecast for 2050 is also not promising since these rates will drastically increase, as the concentration of poverty is shifting from South Asia to Africa, suggesting that it will soon become a predominantly African phenomenon [23]. Moreover, population growth is becoming a threatening pressure; according to the UN

Population Division, the highest regional percentage increase in population between 2013 and 2050 takes place in Africa, from 1.3 billion to around 2.3 billion, with a further 1.9 billion increase between 2050 and 2100 [20].

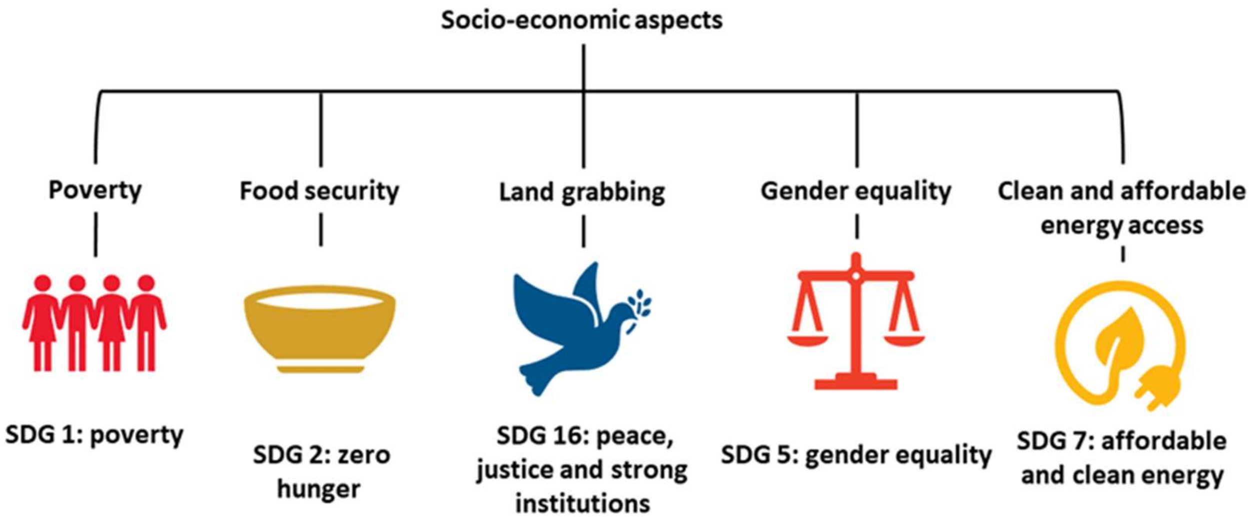

Figure 3. An overview of the socio-economic aspects and the corresponding Sustainable Development Goals (SDGs) included in the following section.

To reduce poverty in Africa, systematic and holistic strategies are necessary. A fundamental strategy is improved energy supply such as decentralized bioenergy provision. As denoted by the United Nations Development Program, "*Energy is central to sustainable development and poverty reduction efforts*" [24]. Currently, 40% of Africans have no access to electricity and this percentage rises to 80% in rural areas [25]. Hence, African agriculture is severely impacted without energy [26]. In this context, depending on the scale, BCSs development could be a win-win situation for the rural population of MADs because it could provide new jobs and new energy sources. Nevertheless, the implementation of bioenergy strategies such as BCSs alone does not assure socio-economic prosperity. When managed unsustainably it can exacerbate the already crucial state-of-play. The most striking outcomes of such mismanagement are decreasing food security (Section 3.1.2), the land grabbing phenomenon (Section 3.1.3), and gender inequality (Section 3.1.4).

3.1.2. Food Security

Currently, 51 countries are listed as Low-Income Food-Deficient Countries, of which 37 are African [27] (Figure 4). Four years after the introduction of the SDGs in 2015, the prevalence of severe food insecurity in the world's population increased to 9.7%, with the highest prevalence measured in SSA where 21.3% of the population is affected [28]. Food insecurity is a result of political, environmental, social, as well as economic factors [29] that create an environment in which it is complicated to develop and maintain a proper food production system. The FAO states that SDG 2 will not be achieved if efforts regarding hunger reduction are not increased [30]. Therefore, the issue of food insecurity must be taken into consideration when planning a BCS on MADs, for instance by choosing low-input agricultural practices that help to spare fertilizers and other input factors for local food crop cultivation.

As mentioned above, sustainable BCSs could provide a new source of income to farmers [31,32]. This would additionally lead to the development of agricultural skills, because cultivating new (bioenergy) crops helps farmers gain knowledge on how to make better use of agricultural resources, and capital stemming from additional income allows for new investments [32]. The latter is crucial to consider, as increasing agricultural productivity is a major priority of SSA [33]. The majority of undernourished people in Africa live off and depend on agriculture, making it essential for achieving a stable livelihood [34,35]. Knowing this, it is expected that agriculture in Africa is used as a means of stimulating development and growth [35]. Nonetheless, Africa's and especially SSA's agricultural productivity is extremely low [35]. Benin, 2016 even describes Africa's agricultural activity as chronically underperformed [34]. Most African smallholders do not have access to pest-resistant and drought-tolerant crops, effective pesticides, and fertilizers [36]. Furthermore, their use of irrigation systems is relatively low, aligning with the general use of agricultural inputs [37]. Means of appropriate processing and storage of food is also not common [36].Therefore, post-harvest losses in SSA occur frequently and mainly take place during storage [38]. The introduction of a BCS could be a leading path towards a more efficient food production system within rural African communities, with numerous positive influences, such as receiving agricultural machinery to realize agricultural self-sufficiency, building up energy systems and generating renewable and affordable clean bioenergy [37].

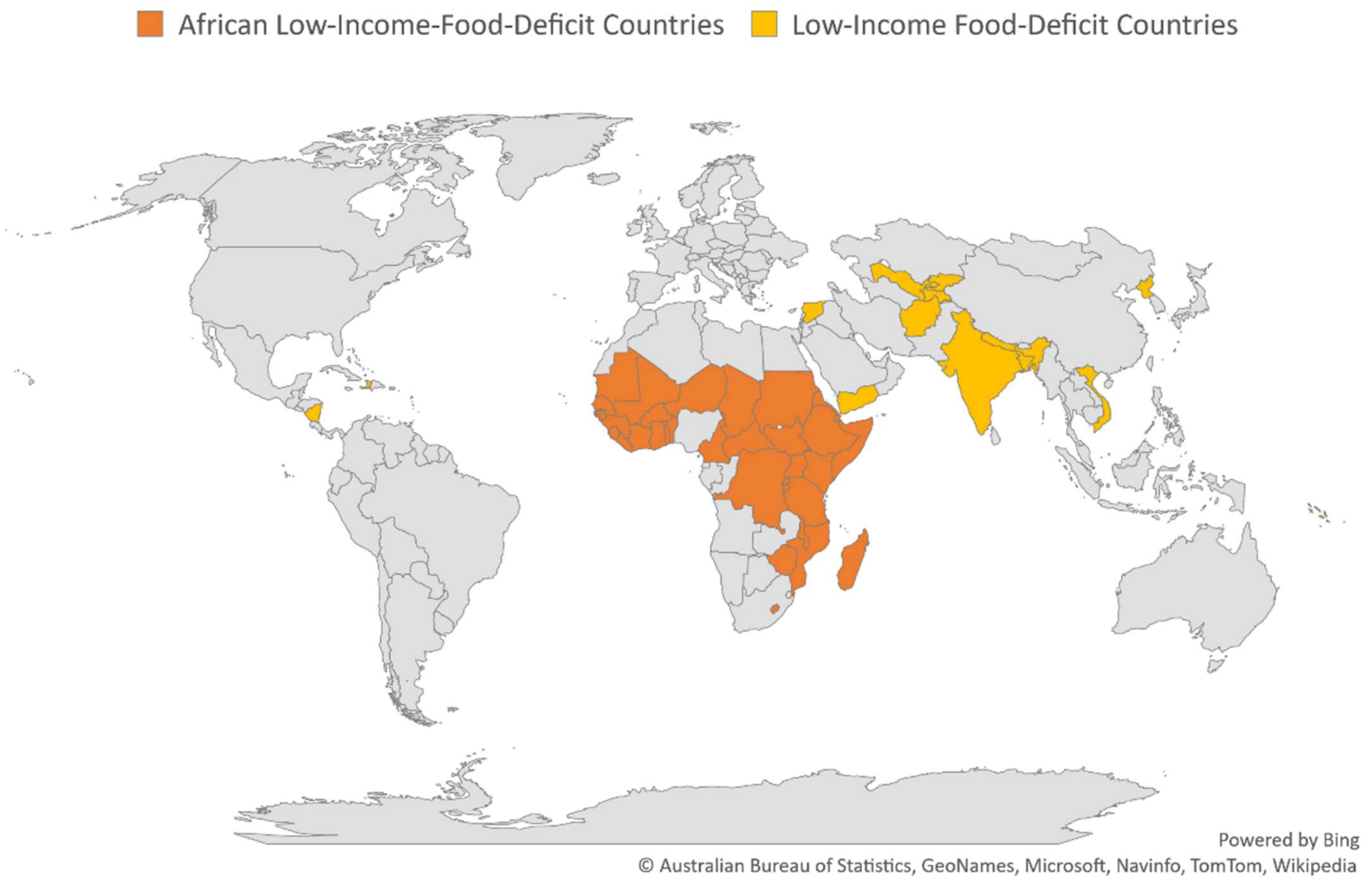

Figure 4. Visual representation of African countries characterized as Low-Income-Food-Deficit Countries (in orange) and countries outside of Africa characterized as Low-Income-Food-Deficit Countries (in yellow). Based on data of the Food and Agriculture Organization of the United Nations (FAO) [29].

While a BCS has the potential of making positive changes for African communities, their possible implementation also indicates threats towards food security. With the challenge of a continuously growing population, the food vs. fuel debate [39] is a crucial factor to consider when discussing the implementation of a BCS—especially in countries that are characterized by food insecurity [27]. Even if marginal land is used and only non-edible crops are grown there (lignocellulosic crops or non-edible oil crops), numerous implications of food security through BCS are conceivable. For bioenergy to have a sufficient impact on climate change, large-scale areas of land would be needed and would result in negative repercussions on food availability [40]. Large-scale land acquisition (LSLA) (Section 3.1.3), due to the increasing demand for socio-economically unsustainable biofuel production, has affected the cultivation of traditional food crops and has hence impacted the world's food prices [40]. Increasing food prices influence food security, mainly affecting poor households [41,42] since an estimated 80% of their budget is spent on food (John Hoddinott as cited in [43]).

3.1.3. Land Grabbing

In SDG 16 (Peace, justice and strong institutions), Action 151 anchored the need to raise awareness of the, "*harmful practices of deforestation and land grabbing*" [44]. Land grabbing is defined as the acquisitions or concessions, whether international or national, that compromise the following, *"violation of human rights, particularly the equal rights of women; not based on free, prior and informed consent of the affected land-users; not based on a thorough assessment, or are in disregard of social, economic, and environmental im- pacts; and not based on transparent contracts that specify clear and binding commitments about activities."* [45]. Since the 2000s, Africa has become the "grabbers hotspot", concentrating the majority of worldwide LSLA [18,46–48]. The ineffective and fragile legal, political, and institutional framework in situ, the favorable biophysical resources, and the lack of existing large-scale, industrialized agriculture and plantations has made Africa the perfect scenario for land grabbing [49].

The drivers of LSLA are to assure foremost food and biofuel security for investors' countries. This comes as a result of the food crises of 2007–2008 [45], and those global agendas are looking forward to reducing fossil fuel dependency and to meeting environmental targets [18,49,50]. To illustrate the dimensions of LSLA, in 2009 the land requests in Mozambique exceeded 20 million ha for biofuels, such as sugarcane and Jatropha, not specified by which stakeholder, which is equivalent to two-thirds of the total arable land in the country [50]. The size of a single acquisition is also increasing, e.g., a documented allocation of 452,500 ha biofuel projects in Madagascar [51]. While these are predominantly areas in rainfed/pluvial climates, with increasing pressure on land use types, it does not seem impossible that such large areas could also be associated with MADs in the future.

The circumstances in which these deals are closed are often shady, and contracts tend to be short and simple compared to the economic reality of the transaction [51]. Deals lack the disclosure of even basic data (e.g., size, nature, and location); they are not transparent, non-consultative, and corrupt [18,49,52]. Even in countries with official institutions for investment, such as "land banks", the records may be inconsistent [51]. Based on the Land Matrix database 2021, there are 1,770,072 ha of land under contract that have been publicly registered since the year 2000, of which the intention of investment is in bioenergy, specifically, biofuels [50] (Figure 5).

The ownership of these investments is dominated by private investors, including urban elites (e.g., politicians, civil servants, and businessmen). The dominance of foreign investment through domestic investors also plays a fundamental role [51]. The dominant foreign investors are the Gulf states, South Korea, China and India [52]. Other representative stakeholders are the United Kingdom and the European Union [18,52–54]. Further investors are Middle Eastern countries, such as the United Arab Emirates, Qatar, and Bahrain, as well as Thailand, Malaysia and Brazil [55].

The outcomes of these uncontrolled land purchases and leases have led to a profound detriment to socio-economic stability [18,45,49,52]. Moreover, LSLA usually occurs in places where there are insecure land rights, and since locals are unable to participate in the decision-making process they suffer from the dispossession of land and natural resources, lack of power, and, even worse, there is no mechanism for relocation or compensation [18,45,49,52]. The panorama in African countries with well-developed policies and strong institutions is also not promising since the strategies to protect the rights of the local community have failed due to weak implementation [18,45,51]. For example, Mozambique policies protect the rights and interests of local communities by including mandatory community consultation when changes in land occur. However, the reality is different, as the national economy is in the foreground, resulting in an unfair, unclear, and exclusive consultation process. Land grabbing does not only affect the welfare of African people, but also presents a worldwide threat since it is creating new patterns of migration, resettlement, and employment [18], with women being the most vulnerable group affected from farmland loss [18,26,45,50,51].

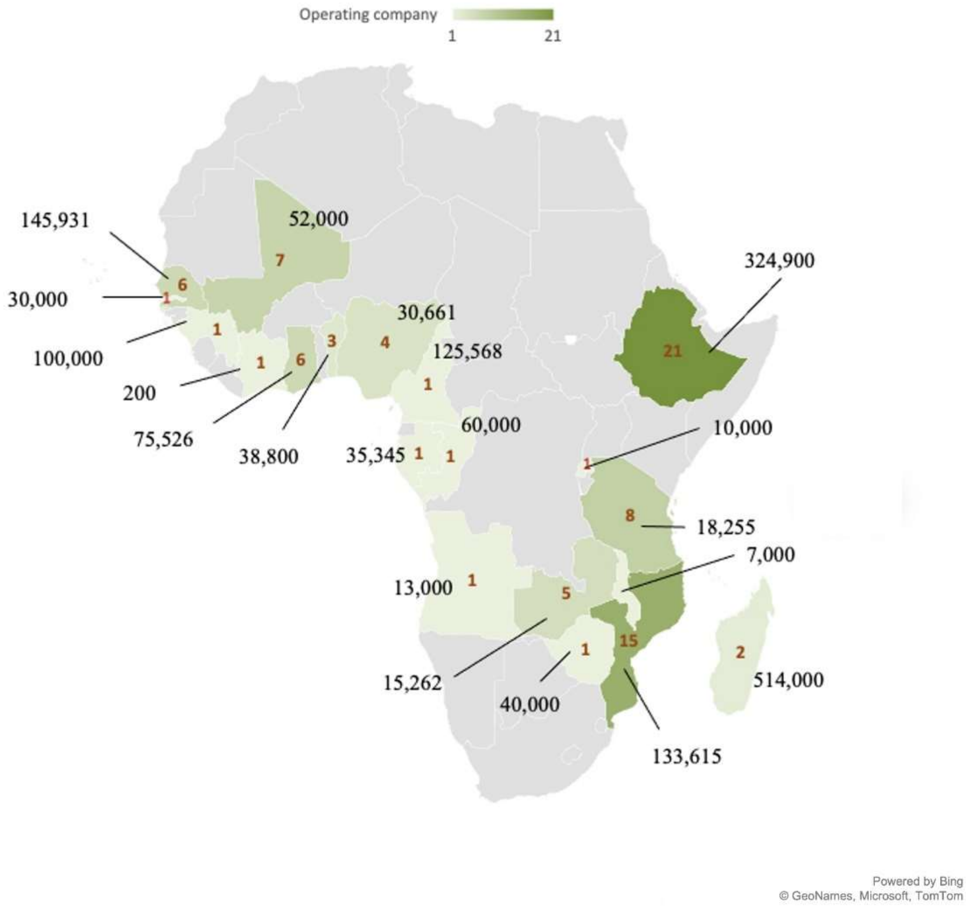

Figure 5. Choropleth map representing the total companies concerning biofuels in each country (numbers in orange), linked to the total area (ha) acquired (numbers in black). Based on the Land Matrix database 2021 [43].

3.1.4. Gender Inequality

Women have a long history of fighting gender inequality [56]. They face social disadvantages that detriment their human development, such as education, health, empowerment, and income-generating activities [23]. In Africa, the gender gap is currently high and progress toward minimizing it has stagnated [57]. This lowers women's possibilities of entering the labor market, attaining higher wages, accessing productive assets (e.g., land, credits), and gaining legal and political rights, among other constraints [23,26,51]. This gender disparity directly affects the agricultural sector, and therefore, the overall economy, since women make up 70% of the workforce and carry valuable knowledge about drylands [26,45,50,58].

The gender implications of the synergy between biofuels and land grabbing are diverse and complex. Women in many African countries have almost no control, ownership and/or participation over the land, as men take full control of the land use and the income generated from it [18,23,45,51,58]. Productive land used for food crops is "easily" taken away from them due to lack of ownership rights, and then allocated for bioenergy crop cultivation [45]. Moreover, in most scenarios, they do not receive any kind of compensation [45]. Further adverse externalities are those for the cash/export crop production, including bioenergy crops, where men are the predominant workforce, while women are involved in food crop and livestock production [26,45,51]. This pattern will indirectly affect women via resource competition and exchange rate effects [59].

Further impacts from LSLA are not always visible and therefore not addressed. For example, in Ghana, for jatropha (*Jatropha curcas* L.) plantations, shea trees have been cut down [45]. These trees provided an important supplementary income for women during the rainy seasons as they served as a significant commodity for cosmetics and cooking [45]. Another example, located in Tanzania, is the restricted access to places where women used to collect firewood for cooking [45]. Women have no other option than to walk longer distances and invest more time in such activities [45]. This time trade-off has a direct impact on households' welfare in several dimensions; a crucial example is because it reduces the amount of time that women can spend on income-generating activities, such as farming [45].

In this section, the main impacts of how women are affected by the synergy of bioenergy crops and land-grabbing were addressed; nevertheless, this was only a brief introduction of a complex socio-economic landscape. BCSs in a low-income but land-rich economy is indeed a viable economic strategy. However, if not implemented sustainably, African women might encounter more disadvantages than benefits in the majority of the cases, limiting their possibilities for improving their agricultural livelihoods [18,23,45,51,58].

3.1.5. Affordable and Clean Energy

Africa is characterized as a low energy continent [60]. Although improvements have been observed, such as combinations of centralized and distributed solutions (in line with the SDG 7 targets), the slow development of energy technology and the steadily growing human population creates an enormous challenge for Africa to meet its rising energy needs [60,61]. According to the African Development Bank, over 640 million Africans do not have access to energy [25], which equals an electricity access rate of 40%, thereby representing the lowest value in the world [25]. The whole African energy sector is considered to be underdeveloped, as, for most people, energy is inaccessible, unreliable, and unaffordable [60]. Therefore, energy poverty, particularly in rural regions, is widespread [60]. The FAO considers the implementation of renewable energies in rural farming communities as a necessary measure to ensure the upkeep of rural livelihoods [62], where bioenergy has the potential to represent a large part of these [40]. The implementation of a BCS on MADs, based on, "*multiple-cropping systems, or systems mixing annual crop species with perennial plants, i.e., agroforestry systems*" [62] could be the first step towards the improvement of energy access in Africa.

In Africa, charcoal and conventional solid biomass-like fuelwood is used for heating and cooking [63,64]. Paraffin candles and kerosene are, amongst other things, used for lighting [63]. Yet the use of these energy sources has several consequences, impacting human health as well as the local environment and causing global environmental issues [33,63,65]. Firstly, indoor smoke can result in infant mortality due to acute respiratory illness [65] and can lead to human health risks in general [33,63,66,67]. In 2012, almost 600,000 deaths in Africa were assigned to household air pollution [61–67].

Secondly, the process produces greenhouse gas emissions and therefore contributes to massive air contamination [63,65], thereby adding to the ongoing process of climate change and deforestation [63]. Thirdly, the activity of searching for and collecting resources such as fuelwood takes away time that could be used to farm and produce goods [63].

Regarding electrification, another aspect to consider is that many people live in villages that are not close to the national grid, which makes it too expensive to partake [68]. Waiting for the grid to reach their communities over the next decade comes at a high opportunity cost, which especially applies to the younger generation [68]. Currently, an increasing number of young people are moving from rural to urban areas [69,70]. The magazine for Africa's Youth, "The 77 Percent", interviews residents concerning this issue and addresses it as the rural–urban migration [70]. The interview confirms the poor access to affordable and clean energy and lists it as one of several reasons why young African people are moving to urban areas [70]. Areas with permanent clean energy accessibility (such as biogas-based heat and electricity) create better living circumstances and opportunities for young people to achieve their goals [70,71].

With the intent to electrify the rural areas, countries have made it their priority to expand the electricity network as mentioned above [72]. They have recently introduced concepts for the decentralized electrification of rural regions using renewable and clean energies [72]. The vision of realizing decentralized energy access through a BCS for people living in rural areas in Africa becomes even more important in the time of the SARS-CoV-2 pandemic. The temperature-sensitive vaccines must reach rural areas in compliance with a cold chain and be stored on-site, where reliable energy access is fundamental [73].

Energy poverty is a profound obstacle to human development and the economy in MADs, since without lighting, human activities are limited to daylight hours [67,70,74]. This reduces the chances of proper education and health, and constrains the agricultural activities that are necessary for food production as well as for access to improved water and hygiene facilities [60,74–76].

3.2. Environmental Review

The environmental review includes the main factors to be considered before the implementation of BCSs on MADs. This section centralizes on the following issues and corresponding SDGs (Figure 6):

- Biodiversity (SDG 15—Life on land) and Climate change (SDG 13—Climate action);
- Water scarcity and drinking water and sanitation (SDG 6—Clean water and sanitation);
- Eutrophication and life below water (SDG 14—Life below water).

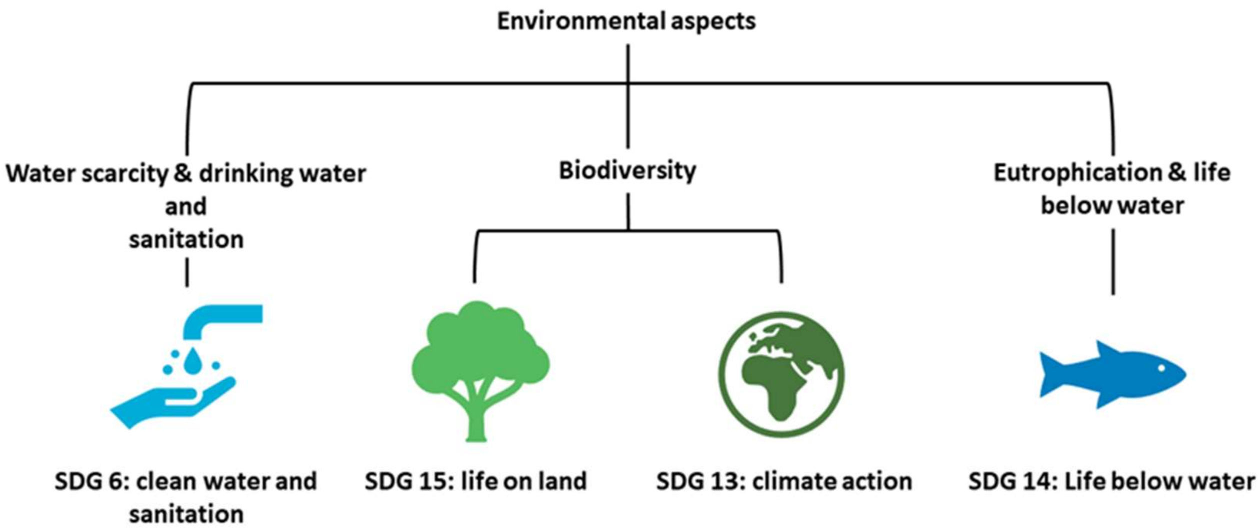

Figure 6. An overview of the environmental aspects and the corresponding Sustainable Development Goals (SDGs) included in the following section.

3.2.1. Biodiversity and Climate Change

In Africa, access to energy plays a central role in the stimulation of local development [20]. Nevertheless, it must be made clear that BCSs can negatively influence biodiversity through land-use change, such as habitat fragmentation or even habitat loss if both the crops and management procedures are not well chosen [77,78]. Until recently, the biodiversity of drylands was not really a scientific focus, but it is becoming increasingly clear that drylands are home to unique species and important crops that need to be protected [79,80]. Biodiversity also plays an important role in terms of social aspects. In Africa, many people are directly or indirectly dependent on the services that nature offers [79], making the preservation of biodiversity essential. This includes, among others, pollination, the conservation of soil, and the mitigation of droughts [81,82] (Table 2). This is also a good example of the often strong interlinkage between the SDGs. Table 2 shows the strong linkage of SDG 15 (life on land) with SDG 6 (clean water) and SDG 14 (life below water) [44].

Table 2. Services provided by biodiversity that people in Africa are directly and indirectly depending on (adapted from [79,81,82]).

Direct Use Value	Indirect Use Value
Water supply	Crop pollination
Water and air purification	Conservation of soil Increased productivity of soil Mitigation of droughts Mitigation of flooding events Management of agricultural pests

Since, according to [79], Africa's biodiversity is decreasing and agriculture, next to climate change, contributes to these losses in large parts [83–86] (which will become even more substantial with an increasing population and demand for agricultural products [83]), the protection of biodiversity must be included in the planning of a BCS. This can be achieved, for example, by selecting biodiversity-friendly plants (flowering plants, perennial plants) or measures (bio-based pesticides, low fertilization, broad crop rotations, mixed crops, etc.).

Not only biodiversity, but equally the agricultural production of goods, in SSA for example, is severely affected by the consequences of climate change [87], which poses a problem for over a half of the working population in Africa as they are employed within the agricultural sector [88]. These consequences are reflected in data which indicate that the global temperature rise has an impact on the agricultural added value [87]. A rise of only 1 Kelvin accordingly leads to a 2.7% reduction in African agricultural production [89]. The cultivation of agricultural crops thereby clearly suffers from the changing climatic conditions and at the same time contributes to biodiversity losses, which makes the urgent implementation of biodiversity-friendly BCSs on MADs very evident.

3.2.2. Water Scarcity

One underlying aspect to consider when implementing a BCS on MADs is water scarcity. In Africa in particular, bioenergy is seen as a feasible development strategy, but precisely in Africa, water scarcity has been a major problem for many years that does not seem to be solvable [20]. In SSA alone, 400 million people are living without access to basic drinking water [90] and this number is expected to further increase given the projected population growth [91]. The Global Environment Outlook (GEO4) believes that by 2025, two-thirds of the world's population will live in places that are affected by water stress [92]. The decisions that are taken today with regard to a more sustainable future must follow up on this increase, as the extent of water scarcity that is being addressed today is nothing compared to what is to come [93]. Concerning Africa, in 1998 researchers stated that by 2030 freshwater resources in South Africa will have impaired by so much that they will be unable to comply with the needs of the people and the industry [94]. Therefore, while the demand for energy and food in developing countries, such as South Africa for example, is increasing, it is of utmost importance to secure water resources on-site, in an already scarce environment [95].

Regarding the implementation of BCSs on MADs, the question arises as to what extent and in what way bioenergy will influence water availability. In 2002, [96] realized that there are only few studies that acknowledge BCS as an upcoming source of increasing water demands. However, this needs investigation with different crops and combinations, and it is extremely important to comply with the connection that water and bioenergy share [97]. A shift from fossil fuels to renewable energy creates an additional liability for freshwater resources [98] and in arid areas, bioenergy crops will quickly enter a water conflict with food crops [99], while at the same time the used water bodies are already revealing signs of overburdening (Section 4.3) [100].

In general, agriculture accounts for 70% of all freshwater extractions [95,101] (Figure 7). The production of bioenergy largely requires biomass [101]. Thus, to grow bioenergy crops, water is needed, and the same can apply to the post-harvest production of bioenergy depending on the energy type [97]. However, there are differences of water requirement and efficiency between the crops that are grown [102]. Regarding the latter for example, sweet sorghum contains sugar and is therefore more water efficient than crops that produce starch, such as grain sorghum [102]. Moreover, the relationship between bioenergy and water is two-sided [97]. Not only does bioenergy need water, but agriculture also requires energy so that a purified and clean water source for irrigation systems can be provided [97].

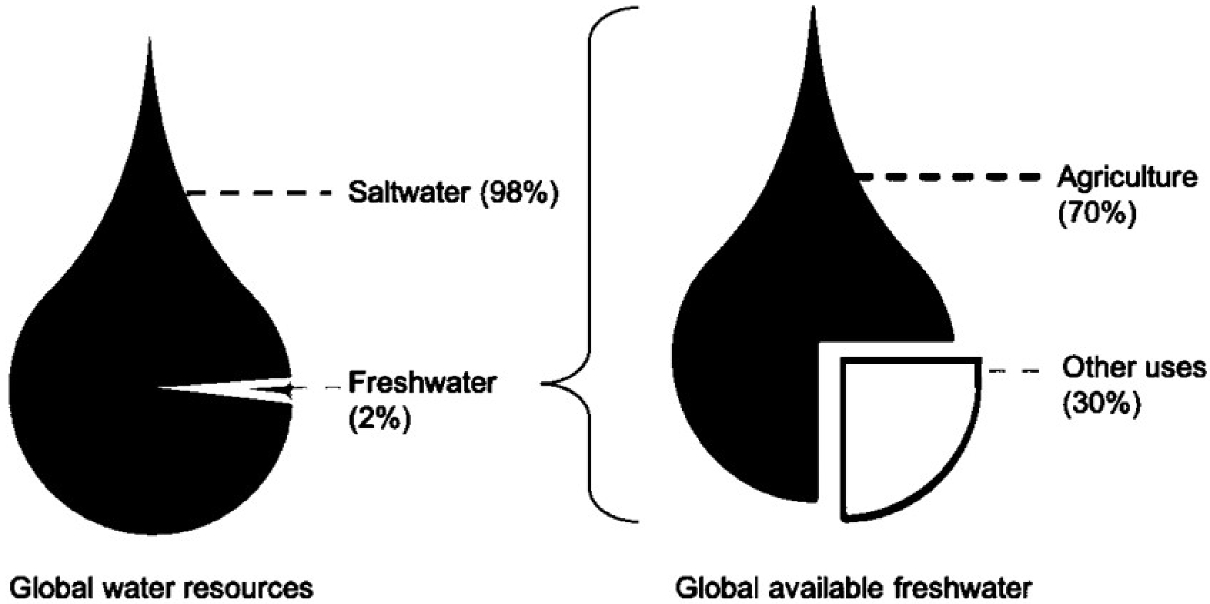

Figure 7. Schematic impression of global freshwater scarcity and the freshwater demand for agriculture already being at a very high level (adapted from [95–101]).

Ultimately, the water resource impacts of BCSs need to be assessed, even though the implementation of a BCS on marginal land is generally considered a helpful tool in avoiding land-use conflicts with food crops [9,103]. Fresh water is a scarce resource as most of the world's water is salt water [9,103] (Figure 7). Only 2.6% of the world's water is freshwater (Figure 7) and much of it is not readily available at is it stored in ice [104]. Therefore, studies have determined that water resource impacts should be included in the considerations regarding the potential implementation of a BCS [105], for example, in South Africa [106]. Thus, to support the successful development of a BCS on MADs, while at the same time acknowledging and conserving water as a vital resource, the use of drought-tolerant crops (e.g., CAM-plants) and rainwater harvesting might be the answer.

3.2.3. Drinking Water and Sanitation

Based on the previous paragraphs, the world is affected by the problem of water scarcity. However, even if there was enough water available for the general population, there is no guarantee that it would be safe for human consumption. For more than 2.1 billion people, contaminated water is the only source of drinking water available [107]. Moreover, 4.5 billion people do not have access to sanitary services [107] and 708 million of them live in SSA [90]. Especially in the time of the SARS-CoV-2 pandemic, it became clear that a decent sanitary system to ensure hygiene and access to safe and clean water is essential for preventing transmission of the SARS-CoV-2 virus (Dr. Sunita Narain, Director-General of the Centre for Science and Environment in India in [108]). The preventive measure of hand-washing with soap for at least twenty seconds several times a day is not feasible for many people in Africa [109,110].

In 2010, the United Nations declared that access to safe and clean drinking water as well as sanitary facilities is a human right of high priority [111], as water scarcity hinders human development [112]. Without clean drinking water and water in general, people cannot stay healthy, work, or perform agricultural activities and consequently, they can never escape poverty [112]. Furthermore, the Water Project addresses the problem of long journeys that women in particular must travel every day to find water that is safe for consumption [112]; they often carry loads of up to 70 pounds on their backs [112]. The United Nations say SSA spends 40 billion hours per year collecting water (United Nations in [112]).

Energy plays an important role in providing clean water for consumption and sanitation purposes [21,107], thereby highlighting the mutual dependency of water and bioenergy. As the world population increases, not only will the demand for water and energy increase, but also the amount of wastewater that has to be treated [107]. In this case too it is necessary to have access to water and energy in order to ensure adequate wastewater treatment [107].

Overall, water is an important resource in Africa that is often not readily available; hence, it is crucial that the plan of implementing a BCS on MADs comes with a people-oriented approach that respects the water problem that African countries generally experience. There are ways in which to decrease the water usage of a BCS as well as ways to increase the local provision of clean water and sanitation services with the help of certain bioenergy crops and decentralized energy systems. These strategies might also be useful in preventing adverse agricultural pollution of the valuable waterbodies remaining in Africa.

3.2.4. Eutrophication

More than three billion people rely on functioning marine ecosystems, fish, and other organisms for their livelihoods [113]. Anthropogenic actions lead to severe pollution events in lakes, rivers, and the ocean [114–116]. A total of 80% of this pollution originates from land-based actions [117]. Today, 40% of the ocean is severely affected by pollution, resulting in the disappearance of coastal habitats and burdened fisheries [113]. With nine important river basins [118] and the adjoining oceans, Africa holds a large number of different water bodies that could be continuously polluted through increasing agricultural and industrial activities, unless necessary measures are taken [115]. Land activities affect adjacent water bodies and their ecosystems [119]. To illustrate, inefficiently used fertilizers washing off from agricultural land (e.g., due to rainfall) end up in near water bodies such as the ocean, rivers, and lakes, causing significant harm to the existing marine organisms [119]. Nitrogen and phosphorus are primary nutrients in conventional fertilizers and an overabundance of them in aquatic ecosystems can launch a process called eutrophication [119]. Eutrophication is the accumulation of excessive nutrients in marine waters caused by agricultural runoffs [119]. The enrichment of these nutrients leads to a massive increase in algal growth. When the algae die they are broken down by bacteria. This process uses a lot of oxygen and subsequently results in a substantially reduced oxygen concentration in the water [117] (Figure 8).

About 28% of the freshwater resources in Africa are impaired by this phenomenon [120]. Amongst others, Lake Victoria [121] and Lake Chivero [122,123] serve as examples for freshwater resources in which eutrophication increasingly emerges as a problem [124]. Concerning oceanic marine environments, research shows that nutrient pollution has a direct influence on the sounds that marine organisms make [119]. Marine environments that are affected by eutrophication appear to be "more silent" when compared to healthy ecosystems [119]. Sound is an important tool for some fish species and invertebrates to find shelter; therefore, the absence of marine noise might lead to diminishing fish population numbers [119].

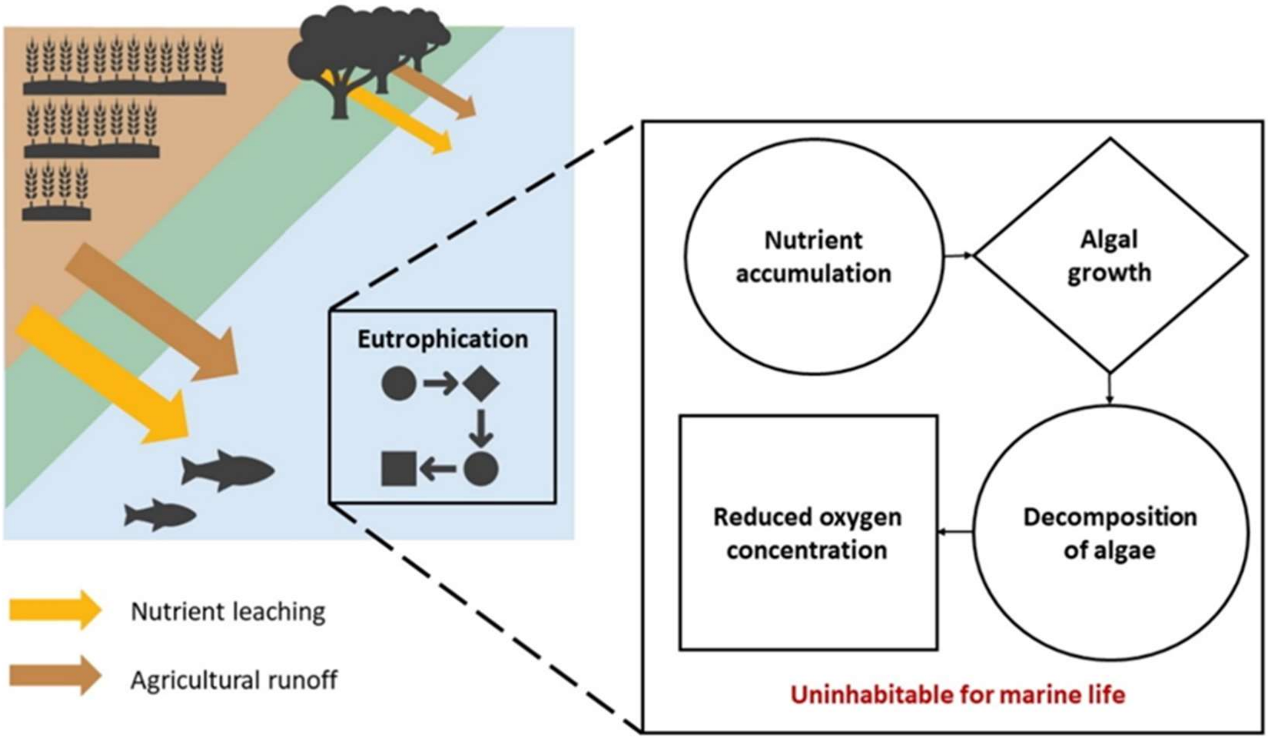

Figure 8. Schematic representation of the eutrophication process caused by agricultural runoff and nutrient leaching, creating a habitat that is uninhabitable for marine life. Perennial crops help reduce both nutrient leaching and agricultural runoff (based on information from [18,62,114]).

Fisheries play a substantial role in the African food sector as they represents 19% of the total animal protein supply [125]. The nutritional value of food is crucial in Africa, where 28% of all deaths are linked to malnutrition [126,127]. Furthermore, fisheries create jobs for communities, especially for those living in coastal areas [125,128]. Consequently, if eutrophication, as well as other environment-detrimental phenomena continue over the next few years, some African households will be strongly affected by the consequences.

While many resources state that eutrophication in Africa is mainly produced through unproperly treated sewage and wastewaters [94], agricultural practices also contribute to this environmental event [129]. The implementation of BCS on MADs would equal the current agricultural activities. Thus, just as eutrophication is associated with the cultivation of food crops, it is equally an aspect that must be considered when cultivating bioenergy crops. If not implemented sustainably, this could have severe negative impacts on existing water bodies [130]. Especially in Africa, where water is scarce and its marine organisms are a vitally important resource, the protection of the rivers, seas, and the ocean is crucial.

4. Key Principles for the Sustainable Development of Bioenergy Cropping Systems on Marginal African Drylands

The literature review that was conducted demonstrated that Africa faces critical socio-economic challenges. Though BCSs alone cannot overcome these challenges, BCSs can contribute significantly to overcome these challenges. Hence, a well-designed and implemented BCS on MAD, which is based on a people-centered strategy, can substantially contribute to achieving the three-dimensional transformation (economic, social, and environmental) that is needed, and therefore, be closer to the achievement of the SDGs. The following key principles provide the foremost recommendations to minimize likely adverse outcomes from BCSs in the main impact categories (Figure 9).

Figure 9. Key principles for the sustainable development of bioenergy cropping systems on marginal African drylands.

4.1. People-Centered-Approach Based Strategies

To overcome Africa's multidimensional challenges, all strategies should follow a people-centered-approach (bottom-up) (Figure 10) instead of a business-as-usual approach (top-down) [131].

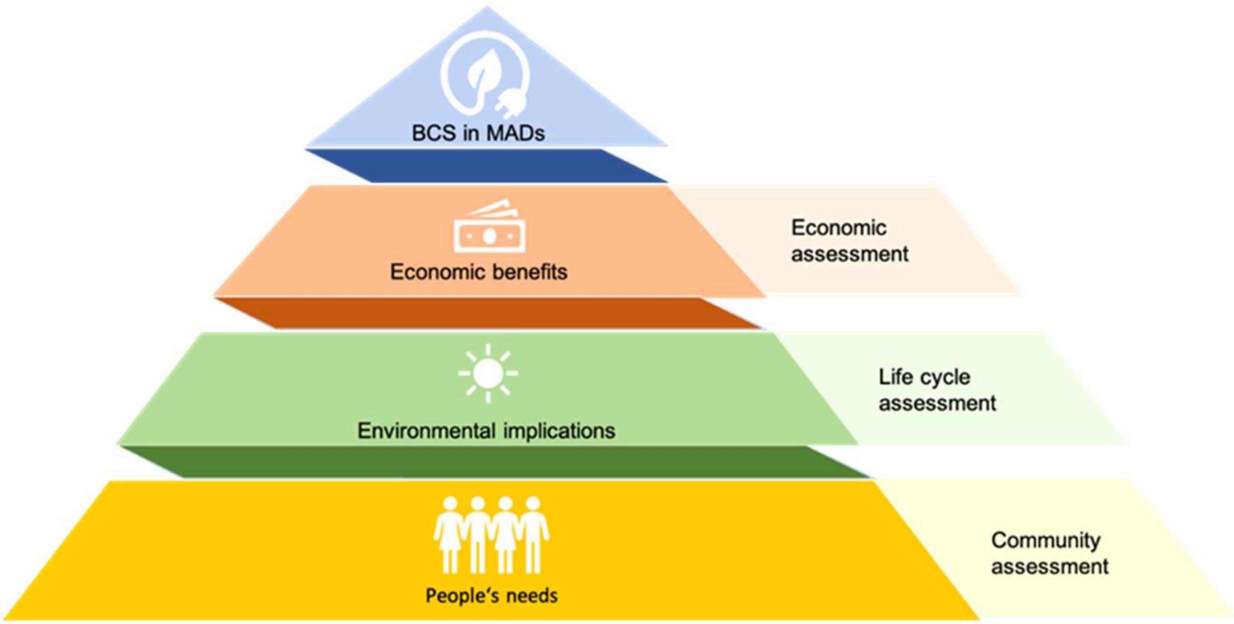

Figure 10. Schematic description of people-centered approach to be considered before implementing new agricultural value chains such as a bioenergy cropping system (BCS) in marginal African dryland (MAD).

This approach considers the dimensions of economic growth, social equity, and environmental sustainability [20,131–133]. Through this approach, smallholders' interests are prioritized instead of profit since it is based on equity and inclusiveness. All men's and women's needs, aspirations, as well as their participation in the planning and decision-making process, are considered before implementing any strategy [20,131,134]. This further implies that opportunities for cooperation between landholders are given to enable the best possible collaboration, for example by sharing large machinery or exchanging newly gained experiences with BCSs. The introduction of BCSs represents a substantial change to the local social system, and therefore requires a well-defined process that considers the impact and reaction of such innovations by members of the system, so that they accept, trust and embrace this innovative renewable energy technology [20,131–133]. A community assessment serves as a tool for such aims [131]. Based on Butterfoss 2007, this assessment involves, "*(1) an evaluation of the current situation in a community, (2) a judgment of what the preferred or desired situation in that community would be, and (3) a comparison of the actual and desired situation to prioritize concerns*" [134]. Conducting such an evaluation before implementation provides a reliable forecast of the possible future scenarios and, consequently, anticipates and minimizes adverse outcomes [51,131,134,135].

Further assessments presented on the bottom-up pyramid that could be considered for the implementation of the BCS in MAD's are the life cycle assessment and economic assessment, used to address the environmental and economic sustainability, respectively. A life cycle assessment serves as a reliable and standardized tool, ISO 14,040 and 14,044, used broadly to evaluate the environmental impacts and energetic performance of biobased value chains. Lastly, an economic assessment is imperative to identify, calculate and weigh the potential costs and revenues of a project. There are several methods that can be applied to conduct such an assessment, such as a cost-benefit or break-even analysis, among others.

4.2. Inclusive and Fair Consultation Process and Transparent Contracts

The consultation process is an essential step before closing any deal regarding the implementation of BCSs, though several African countries usually fail to conduct them successfully [51]. Hence, to mitigate such implementation failures, the following aspects should be considered: (i) *Fairness and transparency.* The local community should have access and be informed about all fundamental data, such as the size of the land acquired, location, stakeholders involved, and the trade-offs needed, among others [51,52]. Likewise, the information should be delivered with anticipation for its careful evaluation and full comprehension by the target audience; (ii) *Inclusiveness.* All individuals should be involved in the decision-making process, including women and other vulnerable groups, such as indigenous people; (iii) *Recorded and signed reports by all participants.* To assure the compliance of the consultation process, and that not only community leaders were consulted; (iv) *Impartial assistance to the participants.* Considering the high adult illiteracy rate in Africa, about 1/3 of adults in SSA cannot read or write [136], and/or that the local language could be a barrier when conducting the consultation, in which impartial assistance should be given to the participants for the full comprehension of the information discussed (e.g., in case of language disparity, translators); (v) *Transparent and disclosed contracts.* The contracts should contain all data concerning the transaction in a detailed manner and be disclosed to the national land register or other public resources. This will serve as a mechanism to achieve transparency. Lastly, long-term planning, monitoring and regulations are needed to validate the compliance of the contract.

4.3. Equal Legal Support and Collective Registration of Community Land

A fair and inclusive consultation process and deal transparency are fundamental to minimize the adverse externalities of the LSLA, but not enough if equal legal support to women and men is not provided. Due to the information asymmetry usually managed in these transactions, smallholders do not understand and/or are not aware of the dimension and implication of such transactions; hence, it is imperative to provide them (including women) with legal support and protection, so that they can obtain a fair deal [51]. The legal support should include at least: (i) *legal literacy training*; (ii) *legal advice*; (iii) *representation in negotiation with government and investors*; *(iv) training on negotiation skills* [51], besides legal actions to assure women's independent access to productive assets, access to credit, and property rights [23]. Concerning land rights, as the literature review demonstrated, LSLA takes place where there are insecure land rights, which make locals highly vulnerable to dispossession, and where the most affected gender is women [23,137]. Hence, one of the main recommendations is to provide equal land ownership rights, and for women this should not be dependent on their civil and marital status [23,137]. Land rights apart from ownership include management, transfer, and economic rights [137]. Fundamentally, this policy recommendation is implemented together with other strong policies and legal frameworks that assure their full compliance. A recommendation for this aspect is the collective registration of community land. Large-scale land registrations in the African context are not the best approach to protect locals' land rights [51,138]. In the majority of cases, the central governments have failed in implementing such a system [138]. The reasons are several, e.g., capacity and the cost of providing the formal land title registration [138]. Therefore, local institutions should effectively undertake intermediate forms of land registration [138]. Since they act at a local scale, registration becomes more easily accessible, cheaper, and they have a better knowledge of their community [138]. Furthermore, collective registration of community land would serve as a good tool to quantify the number of people affected by LSLA.

4.4. Experimental-Serious Games and Raise Female Workforce Demand

The equal participation of women in decision-making processes should be ensured through well-defined policies and local strategies. Scenario-simulation exercises are highly recommended to have a deep understanding of the household level decision-making dynamics and to develop accurate bottom-up strategies that have the potential to be adapted and accepted by the individuals who will be affected. Furthermore, it is a simple and cost-effective tool. These exercises enable a learning opportunity platform for participants, as they acknowledge the economic benefits of a collaborative-balanced decision-making process, and women empowerment is promoted and developed [23]. Likewise, household-level decisions are much more diverse and profitable compared to the male household head alone [23].

Regarding the gender balance of the workforce, as aforementioned, women are the most affected by the introduction of BCSs in terms of unemployment as they are mostly allocated to the production of food crops [23,51]. Thus, it is fundamental to raise the demand for female labor in the sector, as well as to promote their human capital development [23,51]. Policies and well-implemented strategies to create a more gender-balanced society usher in social and economic prosperity [23,51]. A recent report revealed that by achieving gender-equality, African economies could be boosted by the equivalent of 10 percent of their collective GDP by 2025 [57]. To illustrate this, the total productivity factor would increase, as would the purchasing power capacity of all individuals, which would lead to an increase in demand for food, goods, and services [23,51]. Likewise, it is a fundamental strategy to fight poverty and food security [23,51].

4.5. Small scale Bioenergy Initiatives

Small-scale bioenergy initiatives, considered as decentralized bioenergy productions, have proven to be a sustainable alternative for local communities as they provide affordable, modern, and clean energy services for a wide range of essential needs [139]; for example, to power basic household activities and farm machinery, to enable the safe storage of crops, to produce organic fertilizer and energy independence [140,141], and to mitigate the "double penalty" that farmers face as most of them are located far from ports and trade centers, leading to a tremendously high cost for fuel and other inputs, such as fertilizers [20], where African farmers pay from two to six times their global [20]. Furthermore, local stable food security appears to be unaffected and offers new choices in rural communities [20]. The technological implementation of biomass-based electricity access through a mini-grid system with a biodigester would be a feasible option, as it brings together a renewable energy technology that has been deemed as the most appropriate technology for rural communities by the Integrated Renewable Energy Potential Assessment [131,142]. Mini-grids are on-site electricity networks that generate power from solar, wind, hydro and, most importantly, biomass [43]. The products of a biodigester are biogas and digestate, which are synthesized from agricultural residual waste, organic waste and human excreta [142], through a process called anaerobic digestion [143]. Both products have an essential application [142]. The biogas is used for cooking, thereby reducing air pollution [144] (Figure 11), while the digestate serves as a highly qualified organic fertilizer [140,142]. Regarding the latter, this can reduce the amount of nitrogen fertilizer that is needed for a BCS and can thereby counteract nutrient leaching [145] and the subsequent pollution of the groundwater, which accounts for 75% of all drinking water in Africa [146].

Figure 11. Example of a household bioenergy system: biogas digester (**a**) directly linked with a kitchen (**b**), where the produced biogas can be used for cooking (Image credit: B. Winkler).

However, Rupf et al. illustrate that in SSA, the use of crop residues in biodigesters is still uncommon [147]. Households are now encouraged to integrate them as a valuable feedstock into their biodigester systems [147].

Furthermore, depending on the biodigester type, sanitary conditions can also be enhanced, as biodigesters can play an essential role in improving waste management [148].

A technology called the 'Anaerobic Digestion Pasteurization Latrine' incorporates an on-site sanitation system with biogas and fertilizer production [149] by recycling the nutrients present in the waste stream and regaining its energy content [147]. This technology goes beyond energy benefits; it also promotes human development. For example, in South Africa [150], next to a rural school, the electricity generated by the biogas plant enabled scientific experiments for the school students [150]. Another example comes from Tanzania, where the introduction of a biodigester at a university enabled the production of organic fertilizer with the intention of using it for growing a vegetable garden [150].

Small scale bioenergy initiatives in the form of biodigesters thus provide multiple different benefits, facilitating the daily lives of its users, while at the same time, the holistic use of cultivated bioenergy crops is ensured. By using agricultural residues from BCSs on MADs, households experience benefits ranging from an increase in crop yields and health benefits to simple improvements such as *"easy cooking"* [151]. To conclude, beyond the provision of sustainable energy, further representative contributions of a local decentralized bioenergy are: (i) the increase in employment; (ii) human capital, since local communities' benefit from the development of marketable skills and entrepreneurship; (iii) economic self-sufficiency by increasing the income of local farmers; (iv) rural development [20,24,152].

4.6. Agrivoltaic System

An agrivoltaic system (AVS) combines decentralized energy access with the simultaneous cultivation of crops, including bioenergy crops [153] (Figure 12). The implementation of this integrated system would be suitable in semi-arid and arid areas [154,155]. In these areas, the technology can offer the highest added value for both energy production and agriculture [154,155]. The main advantages for the bioenergy crops under the solar panels is the partial shade offered by the panels which reduces soil evaporation and plant evapotranspiration and thus increases the water use efficiency of the crops [154,156,157]. While crops which are already adapted to the harsh conditions of MADs and do not necessarily need shade, the resulting increased water use efficiency reduces the amount of water they require, which is ideal given that water is already a scarce resource. Regarding this issue, an AVS carries the potential of rainwater harvesting [158]. By placing guttering at the lower edge of the solar panels (the solar panels are inclined), rainwater can be caught during rainfall and transported into a water tank [158]. This way, rather than "using" all the water at once, which, due to difficult soil conditions will run off the surface or evaporate quickly, it can be stored to slowly irrigate the crops when needed [158]. Due to the system's suitability to arid regions and the varied uses of the energy produced, AVSs could thus contribute to more progressive development in rural areas in MADs [158]. The above-mentioned usability areas include powering fridges for medicine or post-harvest storage, post-harvest treatments against diseases and pests or energy for clean cooking alternatives [158].

Figure 12. Impression of an experimental agrivoltaic system.

While it is evident that the implementation of an agrivoltaic system is a financial challenge, Randle-Boggis et al. state that there has been a significant trimming of costs of solar photovoltaic systems, making the technology more accessible to smallholders [157]. Furthermore, as the renewable energy sector is gaining importance, governments are receiving the mandate to allocate resources, *"from various sources, such as government funds, investors, and development partners, towards renewable energy projects"* [157]. Yet, mandates regarding the simultaneous use of land for agricultural and energy production do not currently exist [157]. Nevertheless, three pilot projects by the "Harvest the sun twice" project are being implemented to test the financial worthiness, while simultaneously considering the experiences of local stakeholders with the system [157].

4.7. Land-Sharing and Land-Sparing Management System

By implementing the land-sparing management system, i.e., using marginal land for bioenergy and sparing fertile land for food crop cultivation, the competition for land could be reduced [159], as bioenergy crop production would be confined to less productive, abandoned, or degraded agricultural land [160]; however, the competition for water resources would remain in many cases [161]. The solution to this answer could be the implementation of a mixed cropping system, where energy crops and food crops are planted on the same site of land or are integrated as structural elements [160] (Figure 13).

Figure 13. Impression of an intercropping system where maize (*Zea mays* L.) is cultivated for bioenergy production and runner bean (*Phaseolus vulgaris* var. *vulgaris* L.) for human nutrition. The runner bean uses maize as a climbing aid and has little or no negative impact on the yield level of maize. Such practices can increase the land equivalent ratio compared to monoculture farming practices.

This land-management strategy, also known as land sharing, combines food and bioenergy crops in one production system (CFE system) [160]. Various tests have indicated CFE systems to be substantially less resource-demanding than conventional food cropping systems [162–165]. An example for a land sharing management system is agroforestry [160] (Figure 14). In Zambia, an agroforestry approach of quickstick (*Gliricidia sepium* (Jacq.) Steud.) and maize (*Zea mays* L.) has proven to be successful in terms of simultaneous and sustainable food and energy production [166]. Furthermore, agroforestry is known to improve soil fertility, increase water availability, and reduce erosion [167] and is thus an important approach to consider. Further, through intercropping systems, stable jobs are provided, as farmers remain employed for the whole year and do not have to stop working during the rainy season. An example of this is the intercropping of jatropha with peanut and banana in Senegal [168].

Furthermore, the literature shows that intercropping perennial crops with N-fixing legumes can reduce N-leaching [169]. In order to prevent soil nutrient competition between the perennial and the leguminous crop, the literature suggests combining perennials with rooting systems that are far distanced from the surface together with legumes that have a near-surface rooting system [19]. This combination would place the non-leguminous crop into the role pf a catch crop and by doing so would reduce nutrient leaching into surrounding waters [169]. The reduction in nutrient leaching using perennial crops [19] is imperative for the maintenance and improvement of the health of marine ecosystems in Africa, as agricultural activities can impair coral reef ecosystems in nearby shallow waters [128]. Using perennial crops in combination with legumes in BCSs on MADs could therefore potentially preserve African water bodies, their living organisms, and consequently, local fisheries, which play an important social role in Africa. Using an agroforestry or an intercropping system on MADs could therefore be the most environmentally sustainable way to grow bioenergy crops in regions that experience chronic food insecurity. These systems reflect the idea of sustainable intensification [162] as yields are expected to increase without a simultaneous occurrence of negative environmental externalities and, ultimately, regarding the land sharing method, no further land is needed [170].

Figure 14. Impression of an agroforestry system in the dryland regions of Gansbaai, South Africa (Image credit: B. Winkler).

4.8. Potential Species for Marginal African Drylands

While the land-sparing and land-sharing management system already provides an environmentally sustainable base for a BCS on MADs, the selection of appropriate crop utilization pathways (types of energy products) (Table 3) are further important aspects to consider [171]. An ideal BCS on marginal land in Africa should be equipped with perennial crops, ideally perennial crops that have a well-established root system [19]. Perennial crops are known for wind protection, confinement of soil erosion and the maintenance of a healthy, and efficient nutrient cycle and are therefore prominent players for increasing biodiversity efforts [172]. For instance, *Miscanthus* (*Miscanthus* ANDERSSON) is a perennial crop that possesses all the above-mentioned features. It is thus a perfect example of a bioenergy crop that can reduce its cultivation impact in regard to nutrient leaching and subsequent eutrophication [173–175]. However, the cultivation of *Miscanthus* on drylands is not suitable [19].

Table 3. A list of potential candidates to be established on MADs based on their suitability factors and ecological requirements.

Crop Species	Suitability Factors and Ecological Requirements	Type of Energy Product	References
Cassava (*Manihot esculenta* Crantz)	Drought-tolerant, low-input requirements, capable of growing on marginal lands	Heat and electricity (via anaerobic digestion) from the peels and stems	[174,175]
Jatropha (*Jatropha curcas* L.)	Drought-tolerant, suitable for water scarce regions	Liquid biofuel (via fermentation) from the seeds; Heat and electricity (via anaerobic digestion) from the press cake	[176–179]
Agave (*Agave tequilana* F.A.C.Weber)	Minimal impact on food and water resources, able to tolerate high temperatures	Liquid biofuel (via fermentation) from the leaves	[180]
Opuntia (*Opuntia ficus-indica* (L.) Mill.)	Drought-tolerant, suitable for water scarce conditions, counteract desertification processes	Liquid biofuel (via fermentation) or heat and electricity (via anaerobic digestion) from the leaves and stems	[181,182]
Euphorbia (*Euphorbia tirucalli* L.)	Drought-tolerant, high yields in water scarce regions	Liquid biofuel (via fermentation) or heat and electricity (via anaerobic digestion) from the stems	[183]

Due to the predominantly dry conditions on MADs, CAM plants or C4 plants serve as ideal feedstock for bioenergy production [40]. CAM plants are perennial crops that are highly drought-tolerant and show promising yields even when confronted with low water availability. The reason for this is their extensive water storage capacity [40]. Next to jatropha, a plant that is thought to operate the CAM photosynthesis pathway based on its high drought stress tolerance and its handling of water scarcity [176–179], agave (*Agave tequilana* F.A.C.Weber) [180], opuntia (*Opuntia ficus-indica* (L.) Mill.) (Figure 15) [181,182] and euphorbia *(Euphorbia tirucalli L.)* [183] are promising perennial bioenergy crops (Table 3). Opuntia, however, is still considered an invasive species, despite its historic introduction to South Africa in the 18th century. Therefore, its cultivation should always consider the protection of native ecosystems; for example, by avoiding uncontrolled spread around the cultivation areas.

Figure 15. Impression of one of the proposed Crassulacean acid metabolism (CAM) plants for bioenergy cropping systems in marginal African drylands: the perennial multipurpose crop opuntia (*Opuntia ficus-indica* (L.) Mill.), also known as 'nopales', which can grow over 2 m tall.

Aside from being used for energy production, their wastewater from the energy conversion process can be used for yield improvement [40]. Opuntia especially has shown to be extremely adaptable to water-scarce and dry regions as their physiology and anatomy is built to face these conditions [39,181,182]. A source states that the cultivation of this crop is even able to reduce drinking water scarcity (Table 3) [182]. Furthermore, a recent study has shown that agave contributes hardly any pressure on water and food resources [180]. The ideal adaptation to African drylands and their non-competitive character towards food production and water availability makes perennial crops and specifically CAM plants valuable candidates for BCSs on MADs [184]. Several more of these candidates as well as the reasons for their potential suitability of growing on MADs are visualized in Table 3.

It is assumed that the environmental impacts of BCSs cannot be avoided but can be reduced. To do so, the requirements for land, water, and other resources must be carefully taken into consideration when BCSs are planned. Especially regarding feedstock for energy plants that go beyond the household level, the huge demand for biomass needs to be assessed. However, regarding biodiversity protection, it is possible to make crucial decisions based on the type of bioenergy crop. Across MADs, the cultivation of bioenergy crops in accordance with best management practices could even have a positive effect, as a sustainable agricultural cultivation system can counter land degradation [94,185] and increase biodiversity [185]. However, the sometimes-high cost of establishing perennial bioenergy crops could be an insurmountable obstacle in many cases, so additional sources of income would be of great benefit, such as the sale of carbon credits. For this purpose, the amount of organic matter remaining in the soil is considered (rather than the amount of harvested biomass), the carbon of which can be stored proportionally in the soil in the long-term.

4.9. Carbon Sequestration and Bioenergy with Carbon Capture Storage

Another technology that could be implemented alongside large-scale BCS on MADs is biological engineering through carbon capture storage (CCS) [186]. CCS is based on the possibility of fixing atmospheric carbon in biomass as well as in soil and to accumulate it over a number of years. In the case of perennial bioenergy crops, this property is particularly pronounced over the long term; on the one hand, because the root growth of the plants takes place over a long period of time and thus a continuous carbon sequestration takes place [187], and on the other hand, because their cultivation has been optimized for high yield performance [188]. Both, the storage of carbon in the biomass as well as in the soil is an important prerequisite for CCS strategies [186]. However, the carbon sequestration potential must always be considered in relation to the greenhouse gas emissions (GHG) potential, as there are major differences between the various types of plant residues [189]. For example, the higher the lignin content, the lower the GHG emissions potential [189], but only in the very topsoil (0–5 cm) [190]. Again, this is especially true for perennial bioenergy crops (e.g., Table 3), as they are more prone to lignification than annual bioenergy crops [191]. However, since carbon sequestration potential must always be considered in the overall context of ecosystem service performance, social and environmental factors also play a major role [169,186]. Here, there can be large tradeoffs, for example between yield performance and biodiversity support, which was shown in a comparison of maize and wild plant species cultivation for biogas production [192]. For lower-yielding perennial crops, longevity is particularly important to achieve a better GHG emission reduction-potential, compared to highly productive annual crops [192]. Bioenergy with carbon capture storage (BECCS) therefore describes a functioning BCS which is coupled to CCS [193–195]. The BCS can generate bioenergy from biomass and, after pairing it with an appropriate carbon capture method, the emissions caused by the production of bioenergy can be collected on site [196]. In this way, CO_2, which would normally enter into the atmosphere in an uncontrolled manner, can be retracted [197]. After the CO_2 has been converted into a mostly liquid form it can be brought to a number of places such as depleted hydrocarbon fields and aquifers with a joint CO_2 storage potential of about 2600 Gt in Africa and the Middle East [196]. One option is the storage of the liquid carbon in cavities under the earth that are vacant through the previous extraction of oil [197]. Coupling BCS—preferably through perennial biogas crops (Table 3)—with CCS therefore has two advantages: the production of bioenergy and the simultaneous mitigation of CO_2 emissions [197]. In the long term, this could result in a state of net-negative emissions and thus counteract the rising global surface temperature [193]. All over the world and in Africa, efforts in this direction would have a positive effect on climatic conditions. In Africa, extreme arid regions that are affected by climate change or regions that are affected by severe floods could regain milder climatic conditions, which would bring great relief to local farmers [198]. Although Africa is seen as a valuable candidate for BECCS [199], a high level of diligence must be retained when implementing it in an under-developed region as such [199], as the system must remain within the scope of a people-centred approach and also strive for holistic optimization of the ecosystem services [200]. Several sources have stated that many conflicts regarding social aspects, politics, and characteristics of the area to be used have not yet been researched to an acceptable extent [201,202].

5. Conclusions

Africa faces complex multidimensional challenges that need to be addressed by several integrated strategies towards a bioeconomy. The BCSs on MADs could contribute to the socio-economic prosperity of Africa by providing a renewable and sustainable energy source, mitigating soil degradation, and improving rural development. However, the development and implementation of BCSs on MADs must be based on a bottom-up approach rather than a business-as-usual approach. The latter, as demonstrated in this review has brought potential damages to the already delicate state-of-play. This literature review, together with the holistic and interdisciplinary recommendations provided, offers to policymakers and institutions a general overview of the topic's complexity, the main factors to consider, as well as the initial key principles for the introduction of sustainable BCSs on MADs rural communities' system. Ultimately, the sustainable development of BCSs could contribute to the faster achievement of the 17 Sustainable Development Goals in a growing African bioeconomy.

Author Contributions: Conceptualization, P.V.P., B.E.G. and M.v.C.; methodology, P.V.P., B.E.G. and M.v.C.; formal analysis, P.V.P., B.E.G. and M.v.C.; investigation, P.V.P., B.E.G. and M.v.C.; data curation, P.V.P., B.E.G. and M.v.C.; writing—original draft preparation, P.V.P., B.E.G. and M.v.C.; writing—review and editing, P.V.P., B.E.G. and M.v.C.; visualization, P.V.P., B.E.G. and M.v.C.; supervision, M.v.C.; project administration, P.V.P., B.E.G. and M.v.C.; All authors have read and agreed to the published version of the manuscript.

Funding: This study received funding from the University of Hohenheim.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data is provided in the study.

Acknowledgments: The authors would like to express their sincere thanks to Iris Lewandowski for making this research possible.

Conflicts of Interest: The authors declare no conflict of interest.

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