sustainability

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Review

Sustainability Assessment of Bioenergy from a Global Perspective: A Review

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Abstract: Bioenergy, as a renewable energy resource, is expected to see significant development in the future. However, a key issue that will affect this trend is sustainability of bioenergy. There have been many studies on this topic but mainly focusing on only one or two-dimensions of the issue and also with much of the literature directed at studies of European regions. To help understand the wider scope of bioenergy sustainability, this paper reviews a broad range of current research on the topic and places the literature into a multi-dimensional framework covering the economic, environmental and ecological, social and land-related aspects of bioenergy sustainability, as well as a geographical analysis of the areas for which the studies have been carried out. The review indicates that it is hard to draw an overall conclusion on the sustainability of bioenergy because of limited studies or contradictory results in some respects. In addition, this review shows that crop-based bioenergy and forest bioenergy are seen as the main sources of bioenergy and that most studies discuss the final utilization of bioenergy as being for electricity generation. Finally, research directions for future study are suggested, based on the literature reviewed here.

Keywords: bioenergy; sustainability; climate change; carbon emission

1. Introduction

Climate change has been seen as one of the major challenges for sustainable development of human society, and anthropogenic greenhouse gas (GHG) emissions, mainly due to the usage of fossil fuels, have been considered as the dominant cause of the observed change in climate to-date [1]. To address the problem, most of the countries in the world are taking measures to control or reduce their carbon emissions [2]. In this case, promoting the energy transition from fossil fuels to renewable energy sources is one of the main solutions for the world [3], and where bioenergy is expected to play a substantial role within the renewables. In recent years, bioenergy use for electricity and for transport fuels has been growing rapidly, mainly because of higher levels of policy support [4]. For example, IEA predicts that by 2022 bioenergy will be the fourth largest source of renewable electricity generation [5]. However, many factors may influence the achievement of the prediction, and one of these is the sustainability of bioenergy, which is the focus of this study.

A review of the literature indicates that there are many studies focusing on the sustainability of bioenergy. However, the majority of these tend to be rather narrowly focused, looking, for example, at a particular technology or at a specific region. Such studies play an important role in understanding the topic but in our view there remain key deficiencies in the current research, primarily in the following three aspects:

Firstly, as mentioned, most current studies focus mainly on one aspect, such as the environmental impact or the economic influence of bioenergy. For example, Cambero et al. [6] analyze forest-based biorefinery supply chains for bioenergy use via a case study for British Columbia, and show that social benefits, such as job opportunities, are likely to be created; Igos et al. [7] examine rye as the target for a sustainable assessment of the environmental and economic aspects of this source of bioenergy; Glithero et al. [8] set up an economic model to assess farm systems in the UK. Fantozzi et al. [9] present a technical and economic feasibility study for a cogeneration plant for the agro-food industry whereas Efroymson et al. [10] set up environmental indicators to assess the sustainability of biofuel. Few studies put the various aspects together when assessing bioenergy sustainability [11], making it hard for researchers to form an overall understanding of the topic. However, as Robertson [12] proposed, bioenergy sustainability should at least interconnect environmental, economic and social facets. Solomon [13] integrated the three aspects of bioenergy sustainability by using several criteria in order to present a review work. Apart from the three aspects mentioned above, bioenergy sustainability is also regarded as relevant with food security and marginal land use, which is discussed by Tilman et al. [14] and Gelfand et al. [15] respectively.

Secondly, the results from quite a number of studies, e.g., [16,17], draw contradictory conclusions, which does not help stakeholders, including academia and policy-makers, to form a universal view of the sustainability of bioenergy. Fargione et al. [18] claim that whether biofuels offer carbon savings depends on how they are produced. Their study indicates that biofuels made from waste biomass or biomass grown on abandoned land are more likely to achieve carbon reduction goals compared with other forms of bioenergy. Searchinger et al. [19] study croplands in the U.S. and find that the value of using bioenergy obtained from waste biomass is much higher than crop-based bioenergy. By contrast, Hill et al. [20] who analyzed the environmental costs and benefits of both biodiesel and bio-ethanol, found that biodiesel releases less pollutants compared with ethanol. Mohr and Rahman [21] appraised the first and second generations of biofuel, and discussed the challenges for policy in managing the transition.

Thirdly, many studies discuss sustainability-related issues within the context of a specific region of the world (e.g., [22–25]), and where studies that examine bioenergy sustainability from a global perspective are less common. The latter, for example, include Walmsley and Godbold [26] who reviewed bioenergy with a focus on environmental aspects; German and Schoneveld [27] who reviewed the social sustainability of bioenergy; and Miyake et al. [28] who examined integrated land use and environmental aspects for sustainability assessment. However, even these more comprehensive reviews only aim at one or two aspects of the issue, and so far, we have found no study that examines the sustainability of bioenergy in a fully multi-dimensional way.

The main aim of this paper here, therefore, is to develop a systematic review of a wide range of current studies on bioenergy sustainability, and to place these in a multi-dimensional framework and from a global perspective. The overall objectives of this paper are to enhance the public understanding of bioenergy and to provide some potential research directions for future study.

The structure of the paper is as follows: Section 2 explains the research framework and provides an overview of literature reviewed for this study; Section 3 shows the results from this review by visualizing the geospatial distribution of current studies, and by analyzing the sustainability of bioenergy from four different aspects; namely, economic, environmental and ecological, social, and land-related issues. Section 3 discusses the main types of bioenergy and their application forms. Finally, Section 4 presents the conclusions of this study.

2. Research Framework and Description of Target Literature

2.1. Research Framework

To help the public better understand the sustainability of bioenergy in the global perspective from multi-dimensions, this review aims at answering three types of questions as follows:

The first type of questions is region-related with focus on studies with specific regions and the reasons for the choice of the regions. In order to answer these questions, this paper firstly analyzes geospatial distribution of bioenergy studies, which is useful for us to understand current studies of bioenergy sustainability in a macroscopic way. Geospatial distribution analysis can also visualize the density of bioenergy-related studies in a global perspective. Besides, necessary analyses of the major drivers of the geospatial distribution of literature are also studied.

The second type of questions is result-related, that is, which aspects current studies cover and whether the results are sustainability-related. To offer persuasive answers of the questions, the review of current literature covers aspects of bioenergy sustainability and the discussion is focused on the following four aspects: (1) Economic; (2) Environmental and ecological; (3) Social; (4) Land related issues. It should be noted that land related issues mainly include two sub-contents, that is, availability of land and Land Use Change (LUC). The reason for the inclusion of land availability is that big scale of bioenergy development requires a high demand of raw materials from land products, while land itself is also considered as a scarce resource. Therefore, it is reasonable to include land availability when discussing the sustainability of bioenergy. As we mentioned previously, to our knowledge, there is no review that has combined all the four aspects above.

The third type of questions is bioenergy-associated, that is, which types and application forms of bioenergy are frequently discussed by scholars to-date. To provide justified answers to these questions, the type of bioenergy sources and their application forms are discussed.

The research framework of this paper is designed based on the above three types of questions and the flow chart of sustainability assessment progress can be seen in Figure 1. By integrating all these questions, a relatively systematic and explicit review will be presented. Note that the question of whether a form of bioenergy is sustainable or not depends in many instances on the extent to which it is deployed. In this paper, this issue of scale is implicit in most of the papers reviewed, and is a key topic that needs to be kept in mind when discussing the sustainability of bioenergy in its broader context.

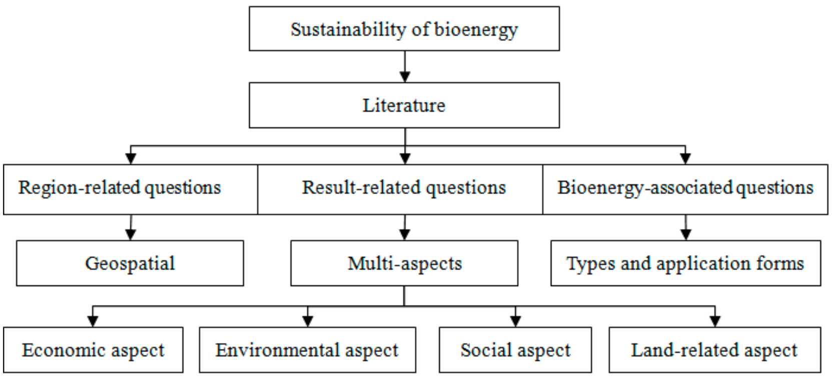

Figure 1. The research framework of this paper.

2.2. Description of Target Literature

As a review work, reviewed literature is the target of our analysis, and the expected conclusions correlate deeply with chosen studies. To make this work persuasive, this review focuses only on relevant literature published on peer-reviewed scientific academic journals. Thus, studies from other sources such as newspaper, reports, blogs and other channels are out of consideration. This paper has reviewed a total of 74 studies on bioenergy sustainability and the publication journals of the reviewed studies are illustrated in Figures 2 and 3 respectively.

Figure 2 indicates that the range of studies is from 2007 to 2018 (with the exception of 2008 and 2009). It is quite clear that bioenergy has been frequently discussed in recent years and soared from 2015 onward, compared with the earlier years. It can thus be inferred that with the increasing concerns on climate change, bioenergy has encountered opportunities for its scale deployment.

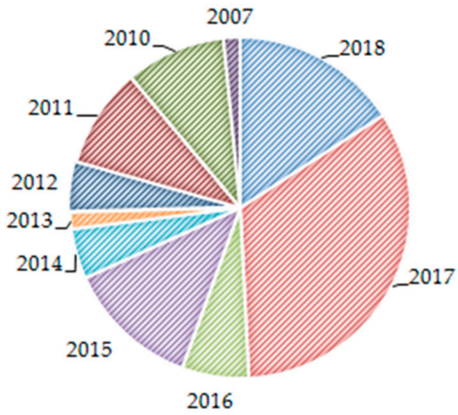

Figure 2. Year distribution of reviewed studies.

Moreover, if analyzed from the distribution of published journals, it is interesting to find that target studies can be obtained in a wide range of journals while journals related to sustainability and/or bioenergy (e.g., the first four journals in Figure 3) no doubt take up a much higher proportion.

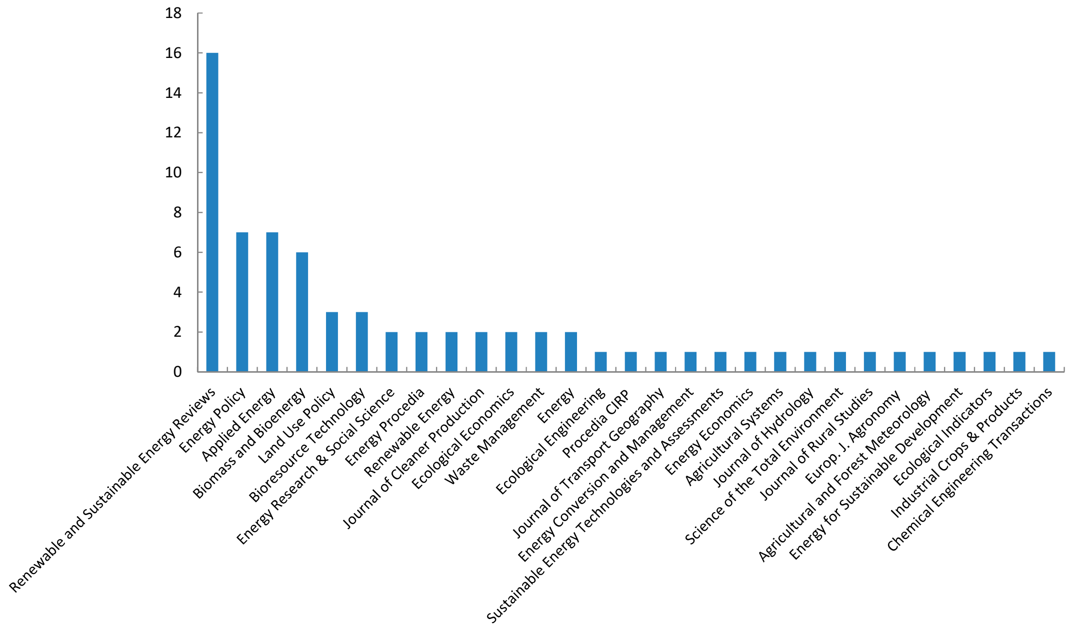

Figure 3. Journal sources of reviewed studies.

3. Review Results

3.1. Geospatial Distribution of Bioenergy Studies

Figure 4 shows the geospatial distribution of bioenergy studies we have reviewed for this paper. From Figure 4, we can see that current studies mainly established in EU countries, with Germany contributes the largest proportion of it (e.g., [29–31]), this may due to the fact that Germany has made a policy—The Renewable Energy Sources Act (German: EEG), which serves as an incentive to promote electricity generation from bioenergy [32]. Other EU members also account for a substantial part of current studies. The reason might be simple: the European directive 2009/28/EC (also known as the Renewable Energy Directive or RED), and the related COM/2010/11 that integrate guidelines for calculating greenhouse gas impact on various bioenergy pathways [33] appeal more to EU citizens and scholars. Southern European regions also take up for a relatively high proportion of bioenergy assessment because many analytical and experimental-based studies are established in this area. For example, Zabaniotou et al. [34] analyze bioenergy systems of Mediterranean areas and promote creation in the agricultural-based bioenergy sector. Manos et al. [35] demonstrate their study more specifically by taking Greece as an example; the results imply that good governance in Public-Private Partnerships is required to achieve the balance among stakeholders, technical solutions as well as financial solutions. Other European countries also appeal researchers' attention but studies on these regions take up for a relatively small proportion. For example, only one of the reviewed works discusses about bioenergy in Russia [36] and mainly concentrates on current status of bioenergy resources such as crop residues, forest residues and municipal solid waste in this country. Steubing et al. [37] assess bioenergy potential in Switzerland and find out that material utilizations, economic factors and Swiss biofuels policy are major constraints for developing bioenergy in this country.

In Asia regions, major studies to analyze the sustainability of bioenergy are focused on China. Four such studies are developed with different focuses, namely, bioenergy systems [38], bioenergy resource potential [39], bioenergy technology [40], economic potential of supply [41]. However, other Asia regions such as Malaysia, India, Iran, and Turkey are less mentioned, as only one or two of the reviewed studies targeted those areas respectively (e.g., [42–45]). The main causes of this phenomenon might be that, as the largest emerging economy in the world, China attracts more attentions from scholars all around the world, and it has made more bioenergy attempts than any other Asian countries, with the purposes both of fossil fuels usage reduction and its responsibility to respond to climate change. Other Asian countries, however, still need more concentration on facilitating bioenergy, for there remains great potential of bioenergy in these countries as well.

The U.S. accounts for a relatively large proportion of bioenergy sustainability assessment in North American regions (e.g., [46–49]), whereas merely one study concentrates on Canada, with the emphasis on marginal land use. A most possible reason is that America actually has sufficient corn-based bioenergy supply compared with its Canada counterpart; and according to Jin and Sutherland [46], from 2000 to 2014, the U.S. bioenergy consumption per capita increased by 38.7%, which roughly proves that bioenergy plays an important part in the country's economic growth.

By contrast, studies in Africa and South America only account for a limited proportion of bioenergy sustainability assessment. For example, Akbi et al. [50] analyze sustainable bioenergy potential in Algeria via bioenergy power-generation technologies, waste resources and industrial wastes; Gonzalez-Salazar et al. [51] analyze bioenergy as well as land use strategies; while Finco and Doppler [52] accomplish their work by integrating bioenergy together with food security and climate change. Compared with the regions that mentioned earlier, Africa and South America regions have more fragile ecological environment (tropical forest systems and desert areas), thus naturally more barriers exist on the way to develop bioenergy. However, it might be a good approach to help bioenergy development in these regions by connecting scattered bioenergy power-generations together to achieve technology enhancement because according to IEA WEO 2017 [53], 10% electricity production in Brazil in 2016 was generated by bioenergy, which indicates the possible scale deployment of bioenergy power-generations in these areas.

We should notice that most of the reviewed studies develop their research in certain areas. (See the map in Figure 4). Thus, due to the uneven distribution of current studies, the authors think that it is a necessity for future researches to pay more attention to Africa and South America regions to improve the global understanding on bioenergy sustainability. Furthermore, South America should be given more attention since this region has tremendous lands covered by farmlands, which can provide a large number of organic wastes, and therefore raw materials for bioenergy production are easy to gather. Moreover, although EU is widely studied in terms of bioenergy sustainability assessment as a whole, it is undeniable that many of the studies actually take Germany as an example as it has published some renewable energy policies and acts as a pacemaker. Therefore, future studies focus on other EU members can also be conducted to assess the sustainability of bioenergy based on their own national conditions.

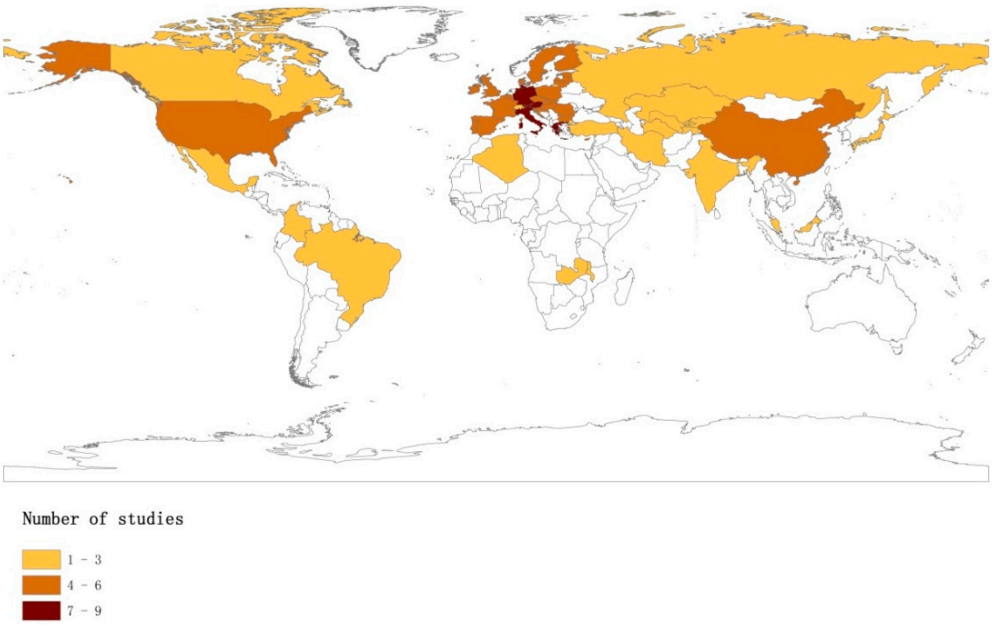

Figure 4. Geospatial distribution of bioenergy studies the authors reviewed.

3.2. Multi-Aspects Analysis

Research aspects in this paper are divided into four parts: economic, environmental and ecological, social aspects, land related issues. Table 1 summarizes the aspects applied in the target literature and the methods used to analyze these aspects. Sections 3.2.1 and 3.2.4 provide more specific analyses on these aspects.

Table 1. Four research aspects in literature and the methods for analysis.

Reference	①	②	③	④	Methods
Awasthi et al., 2017 [54]	√	√			List of economic and ecological impacts through diverse perennial cropping systems(DPCSs)
Purkus et al., 2017 [29]	√				① Technology-push and demand-pull; cost-effective
Hayashi et al., 2014 [55]	√	√	√		① Global Bioenergy Partnership (GBEP), net energy balance; ② LCA of GHG emissions; ③ Change in income, bioenergy used to expand access to modern energy services, etc.
Khishtandar et al., 2017 [44]	√	√	√		Hesitant fuzzy linguistic term sets; Multi actor multi criteria outranking method based on HFLTS
Vasco-Correa et al., 2018 [56]	√	√			① Techno-economic analysis; ② Life cycle assessment
Alsaleh et al., 2017 [57]	√	√			① Theoretical review of market analysis; supply and demand model
Buchholz et al., 2007 [58]	√	√	√		Multi Criteria Analysis (MCA)
Jin and Sutherland 2016 [46]	√	√	√		Causal loop diagram (CLD); IMPLAN (Impact Analysis for Planning)
Tittmann et al., 2010 [47]	√				① Techno-economic model
Kalt and Kranzl 2011 [59]	√				① Techno-economic approach

Table 1. *Cont.*

Reference	①	②	③	④	Methods
Merry et al., 2017 [48]				√	④ Scenario analysis
Pour et al., 2017 [60]	√	√	√		① Cost of electricity (COE) production; ② LCA; ③ social acceptability, job creation, social benefits
Kato et al., 2017 [61]		√		√	② Integrated assessment (IA) model; ④ GRAPE (Global Relationship Assessment to Protect the Environment)
Chitawo and Chimphango, 2017 [62]	√	√			① Cost-benefit analysis; ② Net water requirement, net savings on carbon emissions
Fang et al., 2018 [63]	√				① Cost-benefit analysis
Arodudu et al., 2017 [64]	√	√			① Energy Return on Energy Invested (EROEI); ② LCA
Meyer and Leckert, 2017 [65]		√			② Systematic review
Hennig and Gawor, 2012 [30]	√	√			① Cost and profitability analysis; ② LCA
Liu et al., 2017 [66]	√	√			① Cost-benefit analysis; ② GHG emission model
Fridahl and Lehtveer, 2018 [67]	√		√		① Non-parametric statistical analysis; ② Social constraints on deployment
Santoli et al., 2015 [68]	√				① Discounted Cash Flow
Kang et al., 2018 [69]		√			② The bottom-up energy system, optimization model
Mangoyana and Smith, 2011 [38]	√	√	√		Review and case study
Fuess et al., 2018 [70]	√	√			① Techno-economic model; ② LCA
Durusut et al., 2018 [71]	√				① Techno-economic model
Yang et al., 2018 [72]		√			② LCA
Buratti et al., 2012 [73]		√			③ Input-output analysis
Bartocci et al., 2016 [74]		√			② LCA
Spatari et al., 2010 [75]		√			② LCA
Roos and Ahlgren, 2018 [76]		√			② LCA

Note: ① Economic; ② Environmental; ③ Social; ④ Availability of land (should also include land use change which is not included in this table. Detailed description of land use change is given in Section 3.2.4.).

3.2.1. Economic Aspect

The review of this study shows that 21 studies analyze bioenergy sustainability in economic aspects, which accounts for one of the largest proportion of the four aspects.

Methods of economic assessment are typically techno-economic analysis, net energy balance, market analysis and cost-benefit analysis. Among these methods, techno-economic analysis is most widely adopted and over 30% of the studies mentioned economic aspect (as indicated in Table 1) were based on this approach. The core of techno-economic analysis is the calculation of the internal rate of return (IRR), net present value (NPV), and discounted payback period, which is adopted by many scholars as a preference because of its relatively low threshold and universality. Although popular in most studies, techno-economic analysis has its own drawbacks, especially in its accuracy compared with net energy balance analysis when it refers to energy cost analysis. Hayashi et al. [55] choose net energy balance as one of the indicators in their Global Bioenergy Partnership (GBEP) analysis, which contributes significantly to the holistic assessment of bioenergy.

Energy efficiency is also discussed when assessing economic aspect of bioenergy since high efficiency always means high economic feasibility. Fang et al. [63] estimate energy use efficiency of a potential biofuel feedstock in China and find that the highest observed benefit/cost ratio and economic productivity values for plantation size of 4.0–20.0 hectare in Gansu province and >35.0 hectare in Shandong province, respectively. The authors consider that with the enhancement of bioenergy production, problems caused by growing population in the future might be alleviated. Arodudu et al. [64] develop their work by using Energy Return on Energy Invested (EROEI) and the results show that an extra 1.7 to 1.8 times more of EROEI from corn ethanol and an extra 2.8–3.5 times more of EROEI from corn biogas are obtained. The outcomes of the two studies above indicate that energy efficiency of bioenergy is quite positive.

By using the methods of economic assessment and considering the research results of energy efficiency, many studies draw their conclusions which show a convergent tendency that bioenergy is economical. For example, Fuess et al. [70] observe positive NPV and higher IRR values relative to the minimum attractive rate of return (MARR) (12%) during the implementation of AD-power plants in the reference biorefinery. Besides, when scholars assess the impact factors on bioenergy developments, the price and the cost are the major concentrations. For instance, Tittmann et al. [47] estimate total biomass utilization at a certain range of biofuel prices by applying sensitivity analysis, which is at the range of 18 to 25 million dry tons; Durusut et al. [71] use cost-effective analysis to calculate marginal cost associated with bioheat in Ireland and then provide policy recommendations. For future studies, since economic feasibility is the primary issue for bioenergy sustainability assessment, studies in this field will continue to grow. Moreover, in terms of future energy efficiency analysis, the use of different potential conversion techniques should benefit the bioenergy industry further. Furthermore, at the same time, more focuses are expected to be on some new methods as supplements to the existing techno-economic methods and on how to cut down the costs in a continuous way.

3.2.2. Environmental and Ecological Aspect

Environmental and ecological aspect is the most significant area discussed in current studies as 22 of the reviewed studies analyze environmental related concerns. Life Cycle Assessment (LCA) is extensively adopted as the approach to analyze environmental impact that bioenergy may bring. LCA is defined as "cradle-to-grave" method normally with several indicators such as Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP), which represent different aspects of environmental sustainability assessment and can provide a full-scale simulation analysis on environmental and ecological impacts if data collected is of high quality. When assessing the specific environmental indicators, software packages, such as SimaPro and Gabi are often adopted. Hennig and Gawor [30] evaluate the environmental impact of bioenergy in Germany by applying LCA, and the results show that the use of solid (wood) and gaseous biomass pathways causes the lowest environmental impact; whereas Roos and Ahlgren [76] assess bioenergy systems via the same method. Buratti et al. [73] conduct a case study in Italy by applying Input-output analysis. The authors choose diesel and fertilizers as input parameters of sunflower, rapeseed and soybean during the cultivation, drying and refining progresses, and GHGs emissions as outputs to demonstrate environmental impact of bioenergy. The results show that the current target of EU renewable energy policy was made based on sunflower and soybean chains, instead of rapeseed chain. Chitawo and Chimphango [62] take net water requirement and carbon emission savings as methods to calculate daily water requirement for bioenergy production and savings on carbon emission based on the assumption that electricity production from fossil diesel is replaced by straws when running irrigation water pumps; the results show that the potential fire risk in Malawi will be eliminated and methane gas reduction can be achieved as well by applying bioenergy. Yang et al. [72] combine LCA with water use in their work, and find out that bioenergy production contributes to the majority of the life cycle water use.

Interestingly, carbon emissions related studies hold a dominant share in current LCA analyses. This could be excepted since the justification of low carbon emission is the main driving force of bioenergy production expansion. Therefore, it is necessary for scholars to verify to which extent that a bioenergy product really reduces the emissions in reality [77]. For example, Liu et al. [66] find out that ethanol from bioenergy can significantly reduce GHGs emissions compared with ethanol that obtained from traditional energy forms such as coal, which illustrates that bioenergy usage can reduce total GHGs emissions. Hayashi et al. [55] also take GHGs emissions as an indicator in their LCA analysis and point out that biodiesel fuel is more sustainable overall than diesel. Bartocci et al. [74] indicate that the net carbon footprint of biochar is −737 kg CO_2eq/t. Cherubini and Strømman [78] present a compressive review of carbon balance or carbon neutral of the bioenergy products and their results show that compared with fossil fuels systems, most of studies show that bioenergy systems generally ensure carbon emission savings. However, for some cases of bioelectricity, their life cycle carbon emissions of bioelectricity may be higher than those of other renewable energy, such as hydropower and wind power [78]. Therefore, from the perspective of the overall status, this paper concludes that bioenergy could achieve the carbon saving in reality since bioenergy products are mainly used to replace those fossil energy products.

In a word, these studies, conducted in parts of the world and used various indicators of LCA assessment, have drawn the similar conclusion that bioenergy and related products show positive sustainability tendency compared with other energy forms such as coal and diesel. It should be noted that most of current studies on environmental sustainability of bioenergy are about carbon emissions, which means that the above conclusion is mainly drawn from carbon emission related studies. However, a small number of studies focusing on water consumption show that a large amount of water can be consumed if bioenergy is used for electricity generation. For example, Yang et al. [72] figure out that life cycle water use of woody bioenergy is 40 times than that of crude oil, while this value of charcoal is 20 times more than that of coal. Thus, more studies on water consumption of bioenergy production and other related aspects are required along with carbon emission in future studies.

3.2.3. Social Aspect

Unlike economic and environmental analysis, assessments related to social aspect are relatively scarce, only 7 of the reviewed articles take social aspect into consideration. Multi-index analysis is the most commonly chosen approach, consisting of various indicators such as job creation, income change [54,60]. For instance, job opportunities created by bioenergy related industries are usually seen as one of the social benefits that bioenergy developments bring about. Using questionnaire survey to investigate social acceptance of bioenergy is also a popular method for measuring social sustainability and it is more direct as adopted by Fridahl and Lehtveer [67]. Besides, Carbon Capture and Storage (CCS) technology is another essential method when assessing social impact of bioenergy. Pour et al. [60] develop a framework attached to BioEnergy with Carbon Capture and Storage (BECCS), which involves the conversion of biomass to energy and geological formation of CO_2 produce, transportation and storage, while Fridahl and Lehtveer [67] illustrate their views from another perspective and illustrate its constraints that influences the economic feasibility of BECCS.

The results show that bioenergy developments have benefited the locals a lot because bioenergy associated industries offer a substantial number of job opportunities and the subsequent income increase. Due to the beneficiaries, social acceptance of bioenergy remains at a relatively high level. CCS technology itself is actually a newly-created concept that still needs time to be developed until its maturity. However, it does not matter if researchers can combine CCS with bioenergy, for both bioenergy and CCS are good attempts to mitigate climate change and have been accepted by most stakeholders. BECCS requires more tests and further improvement but ultimately the reduction of GHGs and mitigation of climate change can be a large step forward which is a great contribution of bioenergy.

Thus, future studies might be developed based on an in-depth analysis of the indicators, which requires a clear logical chain about how the job creation happens and to what extend the influence can be. If the logical chain is built properly, a new pathway for social sustainability of bioenergy might be found. And social sustainability indicators might be enlarged since currently major ones are economic growth based, while other indicators such as local environment change can also affect social acceptance, therefore a multidimensional social sustainability assessment framework is required in future studies. BECCS also need more scientific research inputs to maximize the usage of bioenergy because CCS technology has relatively high social acceptance and if widely applied in bioenergy field, public perception towards bioenergy should be more positive.

3.2.4. Land Related Issues

Availability of Land

Two of the reviewed studies take availability of land as an indicator, Merry et al. [48] estimate potential land areas available for bioenergy production and observe the possibility of reduction in land availability. Kato et al. [61] set availability of land as a precondition of bioenergy enhancement and point out that there is a requirement of careful consideration of land availability. Since studies on availability of land are quite scarce we cannot draw a general conclusion of this aspect. The reason for lack of researches on this field might be that some scholars do not consider land issues as a matter or even if they were aware of the importance of land availability they have not thought that there would be impacts on sustainability. However, the main sources of bioenergy are those raw materials that grow on land, and thus use land resource. In many regions with high population density, arable land itself is considered as a scarce resource, coupled with the issues of food security which is also seen as a threat to the availability of land. Thus, in some parts of the world, it is not appropriate to develop bioenergy sustainability assessment without considering the availability of land.

Future studies may be developed based on land availability observation and estimation, and therefore provide parameters for bioenergy sustainability assessment in certain areas.

Land Use Change

Land Use Change (LUC) is also frequently mentioned in reviewed studies, which often causes environmental concerns and one of the factors affecting policy recommendations. Bioenergy usage might cause some environmental impacts on land and therefore lead to the change in land use patterns; moreover, policies associated with bioenergy developments can also affect land use change to some extent. Many scholars have seen the impacts of LUC and in order to demonstrate land related issues of bioenergy more specifically, this section will be developed in a sequence of LUC plus policies (regional and global) and LUC plus environmental concerns.

As indicated in Table 2, the literature review of this paper has identified 23 studies referring to LUC and almost all of them have discussed about either policy recommendations or environmental effects, or both. A number of studies discuss about Renewable Energy Directive (RED) that has been established by the European Commission (EC), and it is noticed that policy driven strategies play an important role in bioenergy development, and mostly are along with LUC (both direct and indirect).

Table 2. Land use change and related aspects.

Year	LUC	Policy Recommendations	Environmental Effects
2018	Kaur et al.; Roos and Ahlgre; Kang et al. [69,76,79]	Roos and Ahlgre [76]	Roos and Ahlgre; Kang et al. [69,76]
2017	Purkus et al.; Khishtandar et al.; Meyer and Leckert; Gonzalez- Salazar et al.; Zabaniotou et al.; Searchinger et al. [29,34,44,51,65,80]	Purkus et al.; Meyer and Leckert; Searchinger et al. [29,65,80]	Khishtandar et al.; Zabaniotou et al. [34,44]
2016	Efroymson et al. [81]	Efroymson et al. [81]	Efroymson et al. [81]
2015	García et al.; Wise et al.; Miyake et al.; Lin et al. [82–85]	Wise et al.; Miyake et al.; Lin et al. [83–85]	García et al.; Wise et al.; Miyake et al. [82–84]
2014	Hayashi et al.; Vázquez-Rowe et al. [55,86]	Vázquez-Rowe et al. [86]	Hayashi et al.; Vázquez-Rowe et al. [55,86]
2013	Scarlat et al. [87]	Scarlat et al. [87]	-
2012	Miyake et al.; Popp et al. [28,88]	Miyake et al. [28]	Miyake et al.; Popp et al. [28,88]
2011	Cherubini and Strømman; Scarlat and Dallemand; Van Stappen et al. [78,89,90]	Cherubini and Strømman; Scarlat and Dallemand [78,89]	Cherubini and Strømman; Van Stappen et al. [78,90]
2010	van Dam et al. [91]	van Dam et al. [91]	-
Total	23	14/23	14/23

Purkus et al. [29] figure out that indirect land use change (ILUC) caused by bioenergy (biofuel production in particular) has become a major issue in EC policy debate; and consequently, an amendment of RED was carried out in 2015 to restrain the proportion of crop-based biofuels in transport sector. Meyer and Leckert [65] also conduct their work with the background of RED, and suggest that policy-makers should consider the interactions with other biomass or crop uses in the context of bioenergy, because ILUC is regarded as leakage effect. Scarlat et al. [87] point out that RED excludes several land categories with high biodiversity value and concluded that biomass should not be acquired from land converted from forest or other areas of high biodiversity or high carbon stock.

Searchinger et al. [80] demonstrate their viewpoint based on the world's current situation and recommended that it is better not to support bioenergy from energy crops and other dedicated uses of land when making a policy. In order to address LUC attached issues, van Dam et al. [90] suggest that policy measures on local, national and global levels should be aligned with the multiple spatial dimensions of biodiversity. Efroymson et al. [81] and Miyake et al. [28] discuss about international climate change policy—Reducing Emissions from Deforestation and forest Degradation (REDD), and attempt to figure out the relationship between bioenergy ILUC concern with the policy REDD. Cherubini and Strømman [78] figure out that standardization in indirect environmental effects may provide the possibility to establish LUC related policies in the field of mitigating climate change.

Besides, in other parts of the world, bioenergy has not quite met their time target, as there are still a plenty of concerns of LUC. We have to mention that, as far as we are aware, main stream argument seems to disapprove LUC associated with bioenergy production, as they consider that LUC brings adverse impacts on the environment. Jin and Sutherland [46] believe LUC plays a negative role in GHGs mitigation, whereas Hayashi et al. [55] combine environmental issues together with economic drawbacks and come to similar conclusion due to LUC caused by biofuel production. Kang et al. [69] think that LUC caused by energy crops cultivation can influence carbon storage capacity of soil and bring substantial variations to the global GHG balance as a result. Apart from environmental debates that related to bioenergy production, LUC itself is also regarded as a matter. Scarlat and Dallemand [89] analyze several regions which show a higher prospect of bioenergy production and consider that ILUC is very uncertain. We may need more technological facilitators such as remote sensing to facilitate sustainable land use planning.

The above analyses show that the attitudes of some people on LUC related to bioenergy are negative for the sustainability of bioenergy or at least contradictory. Therefore, more studies are needed in this area and studies on technology improvements may also be needed to mitigate the adverse impacts that LUC may bring when promoting bioenergy.

3.3. Types of Bioenergy Sources and Application Forms

From the discussion above, we find out that a lot of works analyze the impacts of biofuel production, yet biofuel actually sources from various kind of biomass. In this section, the authors attempt to present an unambiguous classification of bioenergy sources as well as its application forms.

3.3.1. Types of Bioenergy Resources

In our review stage, we find that basically studies mainly focus on the following type of bioenergy forms, which are: crops, biodiesel/ bioethanol, forest/woody biomass, wasted biomass, and aquatic weeds. Major bioenergy sources are covered in our discussion. Crop-based bioenergy requires abundant land to cultivate energy crops; production of biodiesel/bioethanol depends heavily on refinery technologies; forest/woody biomass has the most sufficient supply but is usually accompanied with private-owned or open-field debates; wasted biomass seems to be the most environmentally friendly form of bioenergy with low usage cost, yet social perception towards this kind of bioenergy still needs popularization; aquatic weeds are considered as a brand new bioenergy source with great development potential if more technologies and attentions are thrown in this field.

The number of studies on the types of bioenergy sources reviewed for this paper are shown in Table 3.

Table 3. Types of bioenergy sources.

Types of Bioenergy Sources	Crops	Biodiesel/Bioethanol	Forest/Woody Biomass	Wasted Biomass	Aquatic Weeds
Number of studies	8	8	8	8	1

Liu et al. [66] indicate that energy crops grown on marginal agricultural land are beneficial for the reduction of GHG emissions; and Shane et al. [92] and Qin et al. [39] believe that crops residues can be used effectively to provide more energy. Petersen and Snapp [93] define crop yield without adverse impacts on environment as “sustainable intensification”, whereas López-Bellido et al. [94] and Manevski et al. [95] figure out that currently in most parts of the world, biomass cultivation still encounters issues such as ILUC, and thereby a recession of farmer’s income and biodiversity decline exist.

Crop ethanol is regarded as a major form of bioenergy. Zhang et al. [96] analyze the ethanol production in China, and point out that the production of fuel ethanol is mainly sourced by biofuel crops such as cassava, sweet potato and sugar grass, with about one-third produced from cassava. Qin et al. [39], also focusing on China, estimate that crop residue-based biomass (about 280 million metric tons (Mt)) and energy crop-based ethanol (over 150 Mt) are available each year, which can exceedingly meet the country’s 2020 national target of 10 Mt year^{-1}. Junginger et al. [97] consider import tariffs as the major barrier of bioethanol and biodiesel international trade, and urge that import tariffs reduction can be realized by some specific actions taken by the policy makers.

Organic waste accounts for a substantial part of bioenergy sources, Wang et al. [98] consider that residual wastes can effectively serve human life and will be more important in the future if we use them properly.

We notice that studies on major types of bioenergy are evenly distributed apart from aquatic weeds, this may be due to there are many options of bioenergy, and people tend to use those that are easy to obtain. Thus, aquatic weeds only take up for a small proportion. However, we cannot deny the fact that aquatic weeds have a great potential for generating bioenergy.

3.3.2. Application Forms

There are a number of forms of application for bioenergy, such as bio-gas, bio-diesel, bio-ethanol, bio-heat, bio-power, and combine heat and power (CHP). For example, Matteo et al. [99] and Kraxner et al. [100] point out that it is possible for conversing municipal solid waste or urban forests to renewable fuel, such as bio-gas or other bioenergy. Agarwal [101] and Von Blottnitz and Curran [102] analyze the feasibility of using bio-ethanol and bio-diesel as transportation fuels from the perspectives of net energy and life-cycle environmental impacts. Fantozzi et al. [103] show the technical feasibility for generating heat from biomass and waste. Durusut et al. [71] take bio-heat in Ireland as the entry point, and develop a related model to examine policy impacts against a range of metrics. Manos et al. [104] analyze agro-energy which is basically composed of straw and forests, and point out that in rural areas, public–private partnerships (PPPs) can be a success in the production of thermal and electrical power from bioenergy.

Among these application forms, electricity generation is the most commonly used form for bioenergy and widely discussed by current literature but normally mentioned with CHP technology. Kalt and Kranzl [59] calculate the biofuel production cost as well as electricity generation cost to provide the estimation of CHP feasibility as replacement of fossil fuels in Austria, whereas Tittmann et al. [47] believe CHP producers (e.g., electricity-only producers) are facing significant risk as the threshold biofuel price needed to divert feedstock from electricity to fuel is still relatively low. Santoli et al. [68] assess the social-economic impacts of a CHP plant in Italy by using Discounted Cash Flow (DCF) method. It is obvious that the costs of electricity and the price of biofuel are the major concerns associated with bioenergy electricity production.

In a word, current studies mainly research on crop-based and forest bioenergy, and electricity generation is the most widely analyzed final utilization of bioenergy, which implies that the results of sustainability assessment are outputs under this mode. However, looking forward, aquatic weeds seem to be promising because a substantial number of bioenergy sources remain. CHP has more economic values compared with electricity or heat-only plant. Therefore, a trend for CHP to meet its popularity is likely to come in near future. Thus, future prospective researches should concentrate more on aquatic weeds and CHP as mentioned above.

4. Conclusions

This paper presents a multi-aspect assessment of the current literature on bioenergy sustainability, and sets this within a global perspective. It does this by first analyzing the geospatial distribution of the literature reviewed, and by then classifying the literature against four key indicators of bioenergy sustainability, namely: economic, environmental and ecological, social, and land-related. In addition, the paper analyzes the main types of bioenergy currently under investigation, and sets out their typical modes of application.

From this review, the following key conclusions can be drawn:

1. The majority of authors to date have focused their research on Europe, or on regions within Europe. This is illustrated in Figure 4 and is almost certainly due to approval by the EU of a wide range of strong renewable energy policies. For future research, we thus suggest it would be useful to broaden the existing research areas to cover other regions of the world in greater depth. In particular, we suggest research should increase its focus on Africa and South America regions, because of the scope for connecting scattered bioenergy power-generation systems together so as to achieve technology enhancement; and because a large potential exists for bioenergy

exploitation provided we can deal successfully with issues related to fragile ecosystems in these regions.

2. In terms of findings on the four indicators of bioenergy sustainability focused on here, for economic aspects of bioenergy sustainability, we note that although differences exist among the findings of the studies in this area, the results generally conclude that bioenergy should be regarded positively. In particular, the economic feasibility of bioenergy is noted in most studies; though we recognize that this is very different from saying that bioenergy is cheaper than energy from fossil fuel sources, and from proving the overall sustainability of bioenergy. Note that the relatively high energy efficiency of bioenergy in use, relative to that of some of the alternative renewables, supports a positive view of bioenergy within such an economic sustainability assessment.
3. When considering the environmental and ecological aspects of bioenergy sustainability, authors frequently use life cycle analysis (LCA) methods. Here it is clear that bioenergy can generally contribute significantly to carbon reduction when compared to coal and liquid fossil fuels, such that using bioenergy to replace those traditional fossil energies has the potential at least to help achieve a favorable global carbon balance.
4. On the social aspect of bioenergy sustainability, to-date there has been less of focus within the current literature compared to aspects of bioenergy sustainability mentioned above. Thus, an expansion of research into social indicators could be important for future studies.
5. In terms of the assessment of land related issues, the availability of land itself is less mentioned, and we cannot draw general conclusions due to limited studies on this aspect. On the second and crucial-land related issue of land use change (LUC), here the research is generally extensive, but findings to-date are unfortunately contradictory. This suggests that more research on land-related issues is required.
6. In terms of types of bioenergy sources, and their application forms, the literature reviewed indicates that crop-based and forest bioenergy are the major types currently being researched; and that electricity generation is the main utilization of bioenergy.
7. In terms of more specific conclusions on future research that might be warranted, we note that while the energy in aquatic weeds is generally less concentrated than in many other forms of biomass, they might achieve scale deployment in the future; that CHP has generally a greater economic value compared with electricity production or heat-only bioenergy power plants but seems in our view to be under-researched; and likewise, the important topic of water use in bioenergy production also seems to have received too little attention.

In summary, the multidimensional review of literature given in this paper generally indicates a positive view in the areas of bioenergy economics, though bioenergy is often not the cheapest energy source available; on environmental aspects (though such analyses need to be extended, perhaps particularly on water use); and on social acceptance. However, from a more negative side, we find that studies on land-related issues of bioenergy use are either too scarce (on the availability of land) or contradictory (on land use change) to allow solid conclusions to be drawn, which suggests scope for future work in these areas. Finally, the literature reviewed suggests that understanding the scope for bioenergy sustainability could be improved by a wider geographical spread of studies, in particular for Africa and South America.

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