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Bioenergy Expansion and Economic Sustainability from Environment-Energy-Food Security Nexus: A Review

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ABSTRACT

Bioenergy could have deep effects on economic, social, and environmental sustainability. Thus, the present research aims to review the potential risks and benefits of bioenergy production and consumption. For this purpose, we follow the approach of a systematic review and collect the 105 studies on bioenergy from the Scopus database. The literature suggests that bioenergy is the largest source of replacement of fossil fuels compared to other renewable energy sources and helps to conserve the environment. However, bioenergy production targeted at forest land could have environmental problems as forests are a big source of carbon sinks and biodiversity. Nevertheless, bioenergy consumption is environmentally friendly and releases the least emissions compared to all types of fossil fuels. Moreover, the installation and operational costs of bioenergy are lesser compared to other renewable energy sources. Thus, bioenergy is a cost-effective solution to replace fossil fuels compared to other renewable energy sources. However, bioenergy production replacing the existing crops could reduce the availability of land and water for other agricultural products, which can be responsible for food shortages and rising food prices. Thus, bioenergy production could cause food insecurity with the rapidly growing population worldwide. However, bioenergy could have many other benefits from economic and social dimensions. Thus, the literature has suggested government intervention to achieve net positive benefits from bioenergy production and consumption. Particularly, the literature has suggested public and private spending on R&D activities to find better sources and technologies for bioenergy production and to improve biomass and overall agriculture productivity. Moreover, literature has suggested using marginal lands, other unutilized lands, crop and forest residues, and wastes for biomass production to reduce the pressure on forests and croplands to ensure both food security and environmental conservation.

1. INTRODUCTION

The energy demand is rising worldwide due to the rising population and economic growth. The global population is likely to approach 9 billion in 2050, which may accelerate the demand for nutrition and energy [1, 2]. The most of energy demand is served by fossil fuels, which have heavy environmental concerns for the global economies and are responsible for global warming [3]. Bioenergy is serving a minute proportion of global energy demand [4], which is 6% of the global energy supply as of the year 2022 [5]. However, it is the largest renewable energy source compared to other renewable sources. Bioenergy was the largest source of power and heating before the Industrial Revolution [6]. However, fossil fuels have become the major source of energy after the Industrial Revolution. Hence, the world has realized the importance of bioenergy to protect the environmental effect of fossil fuels, which is expected to significantly contribute to energy needs by the year 2050 [7]. Bioenergy production and consumption carry many potential risks and benefits, which have been presented in Figures 1 and 2.

In the potential benefits, if bioenergy can be produced with the latest technologies to avoid emissions from bioenergy production [8], then bioenergy would help in reducing Greenhouse Gas (GHG) emissions. Particularly, bioenergy can help in reducing GHGs on the energy consumption side if it is replaced with fossil fuels [9]. Contrariwise, the conversion from fossil fuels to bioenergy can reduce the demand and price of fossil fuels [10]. Consequently, the lower price can motivate more fossil fuel consumption. Therefore, the net environmental effect of this conversion is uncertain.

The bioenergy is mostly sourced from oil seeds, starch, and

sugar-rich agriculture products [11]. Moreover, grass and some woody crops can be used for bioenergy [12]. The literature realizes the great potential of bioenergy sources [13]. However, bioenergy production may increase the need for water, which may result in water scarcity [14]. Moreover, deforestation, due to biomass production with forest resources, may put pressure on the natural ecosystem and reduce carbon sinks [15]. Forests are an eminent source to reduce climate change [16]. The conversion from forest to agricultural land could bring a substantial increase in CO_2 emissions and the same may be expected in grassland conversion [17]. Popp et al. [18] proposed a model to make a balance between energy, the economy, and the environment. To sustain the bioenergy, the production chain should be improved. However, biomass production would have an indirect effect on agriculture production by replacing food crops with bioenergy crops [19].

The debate on the relationship between bioenergy and the environment gave birth to the triple concept phenomenon of economic, environmental, and social dimensions of bioenergy [3, 20]. Thus, the literature gave recommendations for sustainable economic growth through sustainable sources [21], which could have optimal economic and environmental solutions. So, the sustainable use of resources would have pleasant environmental outcomes [22]. Otherwise, un-optimal policies would have the environmental, economic, and social problems of the tri-dimensional relationship between bioenergy, food, and environment [23].

In summary, the faster-growing population is fostering the energy demand, which has environmental concerns and is responsible for global warming due to primary reliance on fossil fuels. In the renewable energy domain, bioenergy is the largest source among the other renewable sources. However, bioenergy could have direct and indirect effects on land utilization, water resources, and ecology [24]. Indirect environmental issues of biomass production for bioenergy by deforestation are unclear [4]. Moreover, food security may emerge if agricultural resources are substituted with bioenergy instead of food production [25]. Thus, the triple concept phenomenon including economy, environment, and society may emerge in the relationship between bioenergy, food, and the environment, which demands sustainable practices in the production and consumption of bioenergy. Considering these perspectives, recent literature has reviewed the water-food-energy-environment relationship in the global and regional perspective [26-29] and bioenergy-biodiversity-ecosystem [30]. Still, a gap exists in reviewing the comprehensive role of bioenergy in the energy-environment-food security relationships, which the present study is going to review. Bioenergy production and consumption have both potential risks and benefits. Therefore, it looks pertinent to thoroughly explore all possible dimensions of bioenergy to float useful policies. Thus, the present research aims to review all possible positive and negative effects of bioenergy on land use, water use, food prices, food security, energy security, and economic, social, and environmental sustainability to evaluate the possible risks and benefits of bioenergy comprehensively and to discuss the latest development in the topic as well.

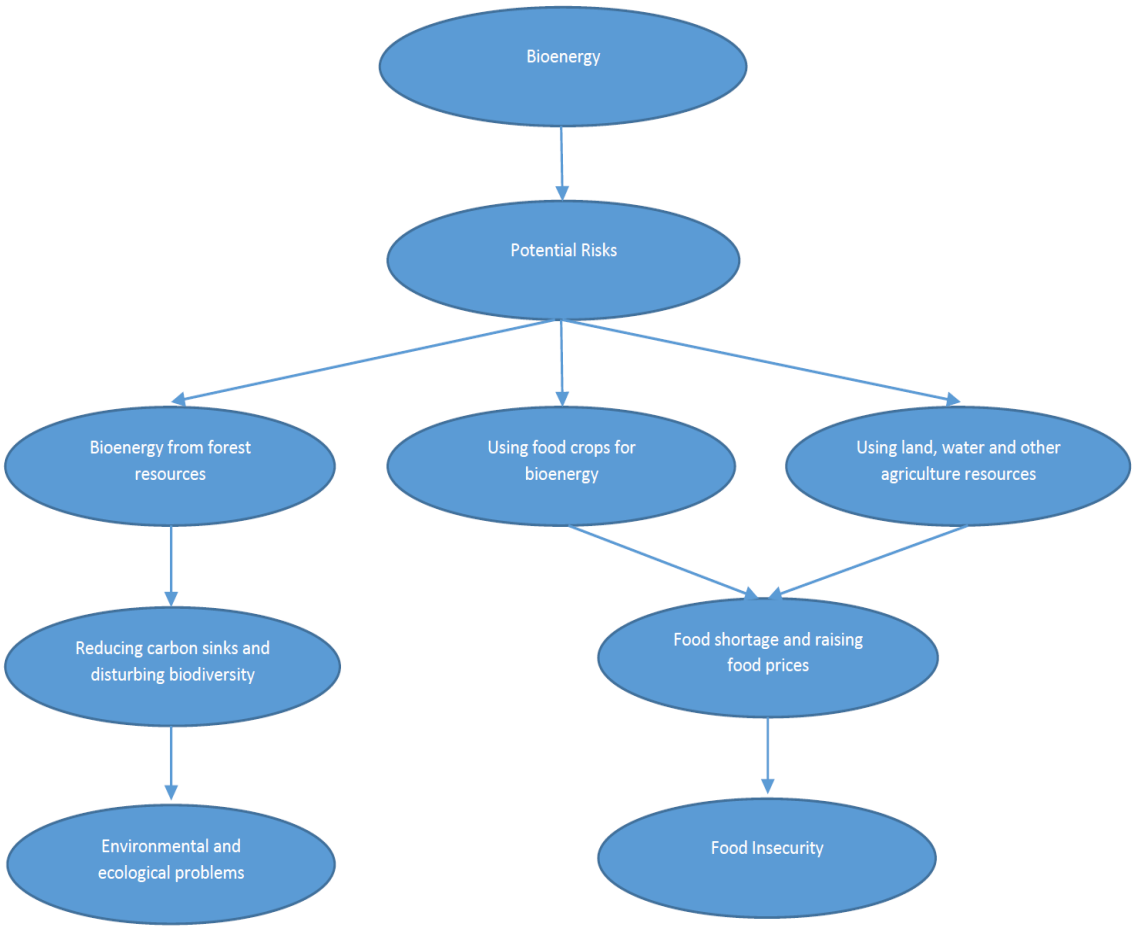

Figure 1. Potential risks of bioenergy

Figure 2. Potential benefits of bioenergy

2. SURVEY METHODOLOGY

Scopus database was consulted to search for the most appropriate study in the context of discussing the role of bioenergy on the environment-energy-food Security nexus. The keywords were searched as ("bioenergy" OR "biomass" OR “bioethanol” OR “biodiesel” OR “biogas” OR “bio-ethers” OR “bio-hydrogen” OR “cellulose” OR “solid biofuels” OR “algae-based fuel”) AND ("environment" OR "environmental sustainability" OR "emissions" OR "water pollution" OR "soil pollution" OR “deforestation” OR “land use” OR “water use” OR “biodiversity” OR “ecology” OR “transportation” OR “forest”) AND (“food security” OR “agriculture productivity” OR “agriculture resources” OR “food prices” OR “food supply”) AND (“fossil fuels” OR “renewable energy” OR “solar energy” OR “cooking energy” OR “transport energy” OR “nuclear energy”) AND (“economic sustainability” OR “social sustainability”). We found 429 articles with the search of these keywords. Then, we start reading the titles, abstract, and keywords of the articles to see their suitability as per the objective of the review to find the scope of the studies discussing the risks and benefits

of bioenergy related to land use, water resources, food prices, food security, other energy sources, and economic, social, and environmental sustainability. We excluded the studies from the review, which did not match the mentioned objectives of the study. In this way, we select 105 articles for review and do thorough analyses of the articles to extract the most prominent findings related to the economic, social, and environmental sustainability of bioenergy production and consumption.

3. THE IMPACT OF BIOENERGY ON LAND USE, WATER RESOURCES, FOOD PRICES

In an estimate, demand for bioenergy is expected to rise triple by 2095 [4]. Thus, this increasing demand for bioenergy would raise the demand for agricultural resources for biomass production. The increasing demand for land would reduce food production on one hand and also would increase the cost of production of bioenergy, which would inflate bioenergy prices [31]. Bioenergy demand is expected to increase to one-quarter of the total global energy demand by 2095 [18]. To meet this demand, the production and supply of bioenergy would create extra pressure on forests and croplands [32]. In another estimate, the demand for bioenergy is expected to increase by $1/5^{th}$ of total energy consumption by 2050 [7]. The production of such bioenergy would require doubling the land use for bioenergy production [4], which could reduce land availability for food production. This situation would result in poverty, hunger, and food insecurity with a given projection of a 9 billion global population by 2050.

To reduce the issue of food insecurity from bioenergy production, biomass should be produced on non-agricultural land [33]. The tradeoff of land allocation for either bioenergy or food production becomes more critical due to the changing cropland usage. Melnikova et al. [32] claim that the use of cropland is increasing over time with both scenarios with stringent or less stringent forest conservation policies. However, Winberg et al. [34] offer a solution of using perennial and woody crops for bioenergy production instead of putting pressure on croplands for biomass production. In this way, croplands will not be disturbed due to biomass production. Nevertheless, this approach could increase an additional burden on the forest sector as wood is already a valuable resource for energy [35]. The additional use of wood for bioenergy could be responsible for deforestation. In the case of forest conservation policy, food prices would increase due to a rise in the demand for agricultural irrigation due to the use of water for biomass production in croplands [36]. Thus, bioenergy production also competes for water resources and could increase water prices [37]. Thus, bioenergy is competing for both land and water resources in the agriculture sector and is responsible for the rising cost of production of food crops [38]. Moreover, Wang et al. [39] claimed that bioenergy production would be responsible for water withdrawals.

Considering the adverse effects of bioenergy production on forests and croplands, some studies recommend to use of marginal lands or other unused lands to reduce pressure on forests or croplands [40, 41]. However, both approaches would lead to higher production costs and lower profits from bioenergy reduction [42], which needs government action to support the higher production costs for bioenergy. Contrarily, Geoghegan and O'Donoghue [43] did a comparative study and found that the production of bioenergy feedstock was more profitable than other uses of agricultural land. Considering both scenarios, market mechanisms could play an important role in the optimal allocation of land use for bioenergy. Moreover, government policies can significantly influence the choice of type of land for biomass production. By providing subsidies for the production of bioenergy crops, governments can provide a competitive edge to producers for the production of bioenergy on unused and marginal lands [44], which could influence land use decisions. In the context of the water scarcity issue in the context of bioenergy, the literature suggested wastewater treatment to resolve this issue [45-48] and to improve the water efficiency in bioenergy production as well [49, 50].

4. IMPACT OF BIOENERGY ON FOOD SECURITY

The global food need is increasing due to the increasing population [1]. Food production should be increased at the same rate of population growth to ensure food security in the future [4]. Food security could be achieved by increasing the efficiency of agriculture inputs [51] and also by increasing efficiency in food processing as well [52]. However, bioenergy production also needs agricultural inputs [53], which can reduce the agricultural resources for food production and lead to increased food insecurity [54]. Thus, bioenergy production reduces food production, which is called an indirect effect of bioenergy on food insecurity [55]. Literature has also discussed the direct effect of bioenergy production on food insecurity, which is defined as a direct use of food crops for bioenergy production [56]. Both direct and indirect impacts would reduce the food supply in the market and could be responsible for food shortages and food insecurity [57].

As discussed above, bioenergy production would create pressure on agricultural resources, which is a challenge for meeting food security. Therefore, bioenergy and food production are facing a tradeoff in using farm inputs [58]. Moreover, rising urbanization along with a desired higher living standards is further expected to amplify food demands as well [59]. However, a substantial portion of food is wasted within the supply chain [60]. Moreover, pests, pathogens, and weeds are also contributing to a great loss of potential food yield before harvest and would escalate food insecurity issues [4]. In a proposed solution, Tagwi and Chipfupa [61] claim that the competition between bioenergy and food can be resolved with presence of the modern advancements in agricultural productivity. In the same way, Tarafdar et al. [62] observed significant improvements in agricultural intensity and efficiency. However, the challenge of meeting global food requirements is still persisting, which will be responsible for food insecurity by the year 2050 [4].

In the bioenergy-food security nexus, there is an urgent need to enhance food security in response to an ever-increasing global population. Food security can only be achieved by a significant increase in agricultural yield and productivity [63]. Moreover, policymakers should prevent food cropland for bioenergy production to ensure food security. Hence, governments should watch the potential tradeoff between food production and bioenergy generation in their resource management [13]. Moreover, there is an urgent need to improve the efficiency of agricultural inputs and to reduce wastage from the whole food supply chain to ensure food security [64].

5. BIOENERGY IS A POTENTIAL SOURCE TO REPLACE OTHER ENERGY SOURCES

A projection has shown that global energy requirement is rising sharply but renewable energy will contribute only one-fifth of energy requirement by the year 2035 [4]. In this tough situation, bioenergy is a blessing for the renewable energy market as it can contribute significantly and help in achieving the sustainable development goals of the United Nations as well [65, 66]. Bioenergy is the biggest source of renewable energy, which carries the 4th position in total energy consumption after oil, gas, and coal [67, 68]. Among the other uses, bioenergy contributes a significant amount to heat and cooking energy including both modern biomass and traditional ways [6]. The sources of bioenergy are forests' residuals, wood, food, and other energy crops from the agriculture sector [69]. Moreover, modern technologies have emerged to use biomass in the cooking industry, which promotes the use of bioenergy for cooking purposes. Thus, bioenergy has more scope for heating and cooking purposes compared to the transport sector. In comparison, bioenergy is efficient for electricity production compared to heat production [6]. Thus, the electricity production should be produced from bioenergy sources instead of fossil fuels.

Horta Nogueira et al. [70] argued that bioenergy captures less solar energy compared to photovoltaic technology. Thus, photovoltaic technology is much better than bioenergy. Moreover, it needs more land for equivalent energy capture [71]. Bioenergy is expected to contribute around one-fifth of total energy consumption by the year 2050 [4] but needs double the land compared to the present use [72]. The demand for bioenergy is constantly increasing, which is expected to rise by 100 EJ in 2055 and by three times in the year 2095 [4]. In this scenario, bioenergy is the future of the world even carrying some discussed negative aspects. On the other hand, fossil fuels are the largest sources of global energy demand but have serious environmental concerns and are responsible for global warming. Therefore, the world has realized the importance of bioenergy as the largest and cheapest source of bioenergy such as bioethanol, biodiesel, biogas, bio-ethers, bio-hydrogen, cellulose, solid biofuels, and algae-based fuel [73, 74]. Moreover, bioenergy is a low-cost substitute for fossil fuels compared to other renewable sources. Thus, governments should support bioenergy production with the least effects on agriculture and forest resources to have optimal benefits.

6. IMPACT OF BIOENERGY ON ENVIRONMENTAL SUSTAINABILITY

Bioenergy has great potential for ecological and environmental protection if resources for bioenergy can be utilized optimally [62]. Moreover, efficient technologies in bioenergy production would reduce pollution to protect against climate change [8]. Most importantly, bioenergy would have the greatest potential for GHG reduction if replaced by fossil fuels and keeping land use and forestation unchanged [9]. Bioenergy depends on various sources including solid, liquid, and gas forms [75]. The environmental effect of bioenergy production depends on multiple factors. For instance, it depends on land use [76], which is a direct effect. The environmental effects can be linked with the fact either production is planned on currently used agricultural land or some unutilized land is focused. If unutilized land is planned for bioenergy, then it may directly affect land use and ecology [77]. In this way, the production of bioenergy crops will not affect the production of other crops to reduce its indirect effects. However, the environmental effects will be directly linked to GHG emissions out of production and consumption of bioenergy feedstock [78]. In comparison, the consumption of bioenergy releases less pollution than fossil fuels and could have pleasant net environmental effects [28, 79]. Moreover, bioenergy is considered a relatively low-cost substitute for fossil fuels [80]. Because installation and running costs of nuclear and renewable energy projects are significantly higher than production of bioenergy [81]. Thus, bioenergy is a quick and cheap way to replace fossil fuels and reduce global warming.

The indirect effect of the production of bioenergy can be more complex than the direct effects. For instance, the production of bioenergy crops may use grassland and forests and could affect the ecosystem and environment [76, 82]. For instance, the land allocated to biomass would raise the total global agricultural land by reducing grassland and forests [12, 83], which would be responsible for CO_2 emissions. Thus, Prieto et al. [6] suggested producing bioenergy with lesser changes in global land use. In contrast, Oláh et al. [10] argue that land usage changes with deforestation minutely contribute to global GHG emissions. They also suggested that the emissions from bioenergy production can further be reduced if sustainable biomass production policies and standards can be introduced and implemented. The forests are a big source of carbon storage and are also balancing biodiversity and the ecosystem [84]. Therefore, deforestation may have a great impact on the climate and environment. However, to protect deforestation from biomass production, agricultural land can be used more efficiently with higher productivity with the help of technological innovations [76]. Therefore, efficient production of bioenergy is needed to play its role in sustainable production and environment [81].

The use of residues from crops and forests for bioenergy production can reduce the need for land for biomass production [78, 85]. Furthermore, the alternative uses of biomass should also be reduced to increase its share in bioenergy production [81]. The use of bioenergy from trees would have a great impact on climate change as trees are a great source of carbon stores [86]. Growing trees takes a long time so it would be difficult to replace the trees in the short run [87]. To avoid this problem, bioenergy should be produced from forest biomass other than trees, i.e., by-products and waste products of timber and paper [88, 89]. In this way, we can reduce GHG emissions from bioenergy without harming forests. In comparison, the ultimate use of fossil fuels or bioenergy depends on market mechanisms and market prices. The price and cost of production would be the right signal to utilize either any fossil fuels or bioenergy. In addition, government policies and support would also determine the optimal use of any fossil fuels or bioenergy resources [90].

In conclusion, bioenergy instead of fossil fuels significantly reduces global GHG emissions if we ignore the indirect environmental effects of bioenergy [79]. Moreover, bioenergy is the best alternative to fossil fuels to achieve a sustainable transportation sector. However, the indirect effects of bioenergy production would have environmental and ecological concerns, which need attention for sustainable production of bioenergy. Thus, the optimal policy and technological solution are urgently needed to have a net

pleasant effect of bioenergy production on the environment and biodiversity [23]. One solution to protect biodiversity is to utilize residues, surplus, and wastes from the forestry and agriculture sectors [78, 85]. Public policies and market mechanisms should also play an equal role in determining the optimal use of bioenergy to ensure economic, social, ecological, and environmental sustainability [23]. By utilizing unused land for bioenergy production with a combination of sound ecological policies, the world can navigate a path toward bioenergy demands. It has a great potential for environmental sustainability if efficient technologies are employed in its production and also land and water resources are utilized optimally. Particularly, bioenergy has great potential to mitigate GHG emissions if biofuels are replaced by fossil fuels in transportation [56, 91, 92]. The largest direct benefit of bioenergy is a significant contribution to reducing GHG emissions by replacing fossil fuel consumption while maintaining unchanged land use [83]. To have the optimal advantage, bioenergy crops should be cultivated on currently unutilized agricultural land and forest areas without harming biodiversity. Otherwise, deforestation would have environmental and ecological problems if bioenergy production is targeted by using forest resources. Deforestation would result in reducing carbon sinks and biodiversity losses [15]. To mitigate the indirect effects of bioenergy on the agriculture sector, governments should promote technological innovations to increase agricultural productivity [76]. Moreover, the utilization of residues from crops and forests for bioenergy production may also have the potential to mitigate the indirect effect of bioenergy production [78, 84, 85]. Besides, governments should also establish high ecological and environmental standards to have maximum positive spillovers of bioenergy to sustain the energy sector in the economies [90].

7. IMPACT OF BIOENERGY ON ECONOMIC AND SOCIAL SUSTAINABILITY

Local bioenergy production has great potential for economic and social sustainability [93, 94]. For instance, bioenergy in its whole supply chain increases job opportunities [95], which could reduce the unemployment rate. Particularly, it has the potential to reduce unemployment in rural areas to support the marginal group of the population [96]. In addition, it can also promote jobs in bio-refinery industries [97]. It would also help in rural development and could help in reducing rural-urban income disparities [98]. Hence, it can reduce poverty and income inequality in the country [99]. Moreover, infrastructure development to support bioenergy production may help other aspects of regional community life and social development [100]. In addition, the bioenergy from solid and industrial waste would reduce solid pollution in both cities and rural areas [101, 102]. Furthermore, bioenergy could significantly contribute to the Gross Domestic Product (GDP) and economic progress of the country. Moreover, it can reduce the pressure on the balance of trade in the net-energy importer economies [103]. It may also help to stabilize local energy prices by reducing the dependence on volatile international fossil fuel markets, which could also ensure energy security in the local economy [50].

The governments of biomass-producer countries are spending on R&D activities to find better sources and technologies for bioenergy production [104], which helps create new industries and markets. Moreover, the governments are also providing incentives for bioenergy production to support this cleaner source of energy, which can also encourage private R&D activities and could develop better and cost-efficient bioenergy technologies [105]. Moreover, bioenergy is also a cost-effective and economically sustainable substitute for fossil fuels compared to other renewable sources [80], which can improve the public health and social and environmental outlook of societies. For instance, installation and operational costs of bioenergy are substantially lower in comparison to other sources of energy such as nuclear and renewable energy projects [106]. Thus, bioenergy represents a convenient and economical approach to replacing fossil fuels and curtailing global warming. The governments should promote the all discussed social and economic benefits of bioenergy by providing financial and non-financial incentives to the producers and consumers of bioenergy.

8. CONCLUSIONS

The rapidly growing global population is exerting huge pressure on energy and food demand, thus presenting significant challenges for sustainability and environmental protection. Bioenergy is a significant source of energy in the renewable energy market and the literature has investigated the different dimensions of bioenergy. The present research has reviewed the bioenergy literature investigating the risks and benefits associated with bioenergy. For this purpose, the Scopus database is consulted and the 105 studies are selected based on a systemic review approach. The findings from the reviewed literature suggest that bioenergy has both potential risks and benefits. The risks include the direct and indirect effects of bioenergy on food insecurity. The direct effect explains that food crops are used for bioenergy production, which may reduce the availability of food for consumption purposes and result in food insecurity. Moreover, biomass production is using land and water resources, which is reducing the availability of these resources for food crops. Thus, bioenergy is leading to food shortages and is responsible for rising food prices, which may increase food insecurity. Another stream of literature discusses the use of forest resources for biomass production instead of agricultural land. However, the use of forest resources is responsible for environmental problems as forests are a big source of carbon sinks and are also responsible for the loss of biodiversity.

The literature has also discussed the potential benefits of bioenergy. On the consumption side, bioenergy is the least polluter compared to all types of fossil fuels. Thus, the consumption of bioenergy could promote environmental sustainability. Moreover, the installation and operational cost of bioenergy is also lower than other renewable energy sources. Thus, bioenergy consumption is the cheapest renewable energy option to conserve the environment from fossil fuel consumption. Carrying these costs and environmental benefits, bioenergy carries the largest proportion of global renewable energy consumption compared to other renewable energy sources. Moreover, bioenergy carries many social and economic benefits for the societies and economies. The literature has suggested that bioenergy production helps in generating job opportunities in rural areas and the bioenergy industries. Thus, it helps to promote social sustainability in reducing unemployment in marginal groups of rural areas. Moreover, it also promotes economic

sustainability by reducing overall unemployment in the economies and supporting economic growth. Besides, bioenergy helps to reduce poverty and income disparity in the communities. In addition, bioenergy production reduces the balance of trade problems in the case of net energy importer economies, stabilizes energy prices, and reduces energy poverty. Moreover, bioenergy helps to generate infrastructure in rural areas, which also helps to raise rural community life and social development. Additionally, bioenergy from solid and industrial waste helps to reduce solid and industrial pollution. Moreover, bioenergy also motivates governments to spend on R&D activities to find new sources and technologies for bioenergy production, which helps in the diversification of the economies by developing new industries and markets in the economy.

The literature has suggested the policy implications to reduce the associated risks with bioenergy and to increase the potential benefits of bioenergy. Following the findings of the literature, we suggest to use of marginal lands and other utilized lands to reduce the pressure on agricultural land, water, and other resources. This implication would be helpful to sustain the availability of land for food crops and also will reduce the pressure on the forest areas for biomass production. In this way, food security will be improved and forests will be saved to protect the environment and biodiversity. Thus, environmental problems from deforestation and food insecurity risks can be controlled. Moreover, crop and forest residues should be used for bioenergy production to reduce the pressure of biomass production on croplands. Moreover, the efficiency and productivity of agriculture inputs should be improved with R&D activities and agriculture waste should be reduced. In addition, the governments should invest in R&D activities and should provide tax concessions and subsidies for R&D activities in the private sector to develop new sources and technologies for bioenergy. Besides, the governments should provide financial incentives to biomass producers to increase bioenergy production, which will help reduce fossil fuel dependence to save the environment from fossil fuel emissions. Moreover, this implication will also help increase the economic and social benefits of bioenergy production. Last but not least, governments should adopt tight ecological and environmental policies to reduce the negative environmental effects of biomass production on forest areas.

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