

**Literature Review of the  
Linkages Between Bioenergy and Nutrition**

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# **1. Introduction**

## ***1.1. Nutrition and bioenergy***

Nutrition security is an important topic in global development discourse, and is crucial to achieving the Sustainable Development Goals; it is particularly critical for SDG2 on zero hunger, although at least 12 of the 17 goals contain indicators that are highly relevant to nutrition (Scaling up nutrition, n.d.). Affordable, reliable, sustainable, and modern energy access for all is also recognized in Agenda 2030 under SDG7, and likewise interacts with the achievement of almost all other SDGs.

Modern bioenergy, a form of renewable energy produced from organic matter, has the potential to aid in the achievement of the SDGs, when managed in an appropriate and sustainable manner. Bioenergy is a necessary component of low-carbon development strategies and will also be crucial for ensuring energy access for all. Bioenergy makes up part of the broader bioeconomy, which is the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes, and services) within and across all economic sectors and enable a transformation to a sustainable economy (Global Bioeconomy Summit Communiqué, 2020).

## ***1.2. Scope***

While the nexus between bioenergy and agriculture, food and diets seem apparent, an active discussion has not yet taken place on the specific good practices across bioenergy value chains that could positively impact nutrition security. This literature review was developed for both the nutrition and bioenergy communities to acknowledge and leverage this nexus and the opportunities that it presents to improve nutrition security.

The aim of this literature review was to collect and analyze the available evidence most relevant to the relationship between bioenergy and nutrition. The literature review identifies the various positive interlinkages between bioenergy and nutrition that have been explored in existing research, especially implications on food and nutrition security, and the impacts on agricultural land and soil quality, which could influence nutrient contents of food, and other aspects of health related to nutrition. It is intended to highlight good practices in bioenergy production that can have positive impacts on nutrition.

## ***1.3. Methodology***

This study was conducted through a review of recent literature on bioenergy and nutrition. Articles analyzed for the literature review consisted of peer-reviewed papers, technical papers, and documents prepared by nonprofit organizations and governments. In total, 47 articles were used in the development of the literature review (see Appendix for full list). 42 articles were identified through internet searches, specifically Google Scholar, using keywords such as: bioenergy, nutrition, nutrition security, diet diversity, diet quality, food security, health, indoor air quality, improved cookstoves, biomass, biochar, digestate, soil quality, and climate-smart agriculture. While there was no specified timeline on the articles that were chosen and analyzed, publishing years ranged from 2006 to 2021. Articles and papers that did not specifically mention nutrition, diets, or food security were still analyzed, especially as they pertained to soil quality and indoor air pollution. Remaining articles were provided by the Partners and Observers of the Global Bioenergy Partnership (GBEP), after a request for specific examples and good practices at national

and local level. An appendix of all articles read and analyzed for this literature review has been included at the end of the document.

#### ***1.4. Structure***

The literature review has been organized according to the stages of the bioenergy value chain and how they relate to nutrition: 1) bioenergy production; 2) bioenergy byproducts; and 3) bioenergy use. At each stage, the potential positive linkages between bioenergy and nutrition are presented, as observed in the literature, and examples of good practices that can safeguard or enhance nutrition security are provided where available.

## 2. Links between bioenergy production and nutrition

The first stage along the bioenergy value chain that was explored for this literature review was bioenergy production. Within this section, elements of how biomass production for bioenergy, including phytoremediation and intercropping, may affect nutrition were explored, as well as the indirect impacts on nutrition security from income diversification. From the various sources, it can be determined that phytoremediation using bioenergy crop species has a large potential impact on nutrition, although safeguards need to be in place to mitigate potential negative consequences. Integrated biomass production systems can also have positive effects on soil quality and crop yield, although research linking these factors with nutrition is limited. Income diversification from the production of biomass for energy could also have varied indirect effects on household nutrition security. Overall, the available research shows that there are clear implied links between bioenergy production and nutrition but that they are in some cases indirect or ambiguous, and require further exploration and research.

### 2.1. Phytoremediation

Phytoremediation – the removal of heavy metals and other pollutants from soils using green plants – has been widely accepted as a cost-effective environmental restoration technique and as an alternative to engineering procedures that are more damaging to the soil (Gomes 2012). Several studies have explored the use of various perennial bioenergy crops for phytoremediation to prevent or reduce contamination in the soil, which can be passed along the food chain, negatively impacting nutrition (Yan et al. 2020). These bioenergy crops can be planted as buffer zones to reduce leaching of pollutants from contamination sites or on already contaminated land as remediation for future use.

Several perennial bioenergy crop species have been identified as capable for use in phytoremediation, including *Miscanthus*, *Ricinus species*, *Jatropha curacas*, *Populus species*, and other members of the *Salicaceae* family (Yan et al. 2020; Pandey et al. 2016). Within the United Kingdom, studies on contaminated brownfield sites found that mixed poplar and willow, together with *Alnus* species, were effective at reducing zinc and cadmium levels (Gomes 2012; Rowe et al. 2009). Similarly, in the northeast United States, willow has been widely developed for bioenergy and bioproducts, and interest in the species for phytoremediation has increased in recent years, as willows have been shown to uptake heavy metals and organics from soil, facilitate the breakdown of organics to non-toxic compounds, and control water dynamics (Volk et al. 2006). Other perennial bioenergy crop species such as *Miscanthus* have great potential for phytoremediation, as they increase soil carbon content and promote soil microbe activities and diversity (Pandey et al. 2016; Emmerling et al. 2017). Wetland species, such as water hyacinth (*Eichhornia crassipes*), may also be used to remove heavy metals from livestock wastewater, allowing for its use in irrigation of cropland; the subsequent contaminated biomass can be used for bioenergy either through incineration or anaerobic digestion (Hejna et al. 2021).

As with many other remediation strategies, phytoremediation requires forethought and safeguards to avoid potential negative consequences, which could include loss of biodiversity through increased energy crop cultivation, nutrient loss in soil, and intensive water requirements for energy crops (Pandey et al. 2016; Gomes 2012).

Where favourable conditions exist for phytoremediation and subsequent use of biomass for bioenergy, this solution has the potential to improve the quality of soils and remove contaminants that could pose a threat to human health. Research is ongoing on the most suitable genotypes for phytoremediation in different ecosystems, and this is an area that should be explored further.

## ***2.2. Integrated biomass production systems***

Novel biomass production systems may allow for the sustainable concurrent production of biomass for multiple purposes in agricultural and forestry landscapes. They include crop rotations, flexible crops, intercropping and agroforestry (IRENA, IEA Bioenergy, and FAO 2017). These integrated systems in some cases can mitigate land use impacts and enhance ecosystems services, thus improving the potential of the agricultural ecosystem to produce nutritious food.

Intercropping is one such approach that has the potential to improve soil quality. Intercropping is a multiple cropping technique that has long been applied worldwide, as it has been shown to maintain long-term productivity and sustainability (Ma et al. 2017). Nitrogen is vital to proper plant growth as it is a major component of chlorophyll and amino acids, the building blocks of protein. Nitrogen is often one of the most limiting factors in plant growth and crop production, hence the application of nitrogen into soil is essential to ensuring crop production to meet growing agricultural demand. Intercropping as a mechanism to ensure nitrogen content of soil exhibits great potential (see e.g., Cong et al. 2014). Additional evidence suggests that intercropping energy crops such as sugarcane can improve functional diversity, crop yield, and soil quality (Singh et al. 2020). Intercropping of cash crops with nitrogen-fixing crops can enhance soil fertility, reducing soil degradation; an example is the short rotation coppicing tree *Gliricidia sepium* that is intercropped in the tropics with cash crops to reduce soil erosion, while its prunings are used as green manure to increase or stabilize cash-crop yield (see e.g. Makumba et al. 2010; Phiri and Akinnifesi 2000). Intercropping also minimizes weeds that draw large amounts of nutrients and water from the soil, diverting resources from the crops (Singh et al. 2020). A study conducted by Ma et al. (2017) examined the effects of the intercropping chestnut trees in tea plantations on the seasonal dynamics of soil nutrients, soil enzyme activity, and tea quantity and quality in a temperate region in China. The study found that intercropping increased all the soil nutrients measured, including total nitrogen, total potassium, total phosphorus, and hydrolysable nitrogen. The study additionally concluded that intercropping increased tea length and weight and the content of theanine, while increasing contents of amino acid and catechin content – the primary compound responsible for the claimed health benefits of green tea, including its anti-inflammatory and antioxidant properties.

Crop rotations of food crops with other crops with multiple uses – such as fuel, feed and biomaterials – can also have positive impacts on soil quality through, for instance, nitrogen replenishment and reduced soil erosion. For example, the use of alfalfa, a deep-rooted perennial legume, in crop rotation with corn has been extensively studied in the US and has demonstrated increased soil nitrogen content, reduced nutrient run-off and reduced soil erosion (Jung, 2010).

Whether these improvements in soil quality and crop yield have a positive impact on nutrition needs to be explored further, and this topic presents much potential for future research.

### ***2.3. Income Diversification***

Bioenergy can indirectly impact nutrition security through the diversification of income within rural and low-income communities. Through appropriate bioenergy policies, farmers may be able to grow energy crops in addition to crops for food (Sakai et al. 2020; Faße et al. 2014; Rogers et al. 2016). Farmers may also have the opportunity to grow energy crops on degraded or marginal land not suitable for food production or lease portions of their land for energy crop production, for a profit (Campbell et al. 2008; Shortall 2021). Farmers may also be able to valorize previously discarded residues or wastes thus further improving overall farm revenues. One case study comes from Kenya, where the fruit of the Croton tree (a tree traditionally planted for shade and firewood) is collected for biofuel production, providing additional income for over 6000 farmers (SEI 2020). Furthermore, the expansion of the bioenergy sector can facilitate employment opportunities and access to green jobs, particularly within rural communities (Sakai et al. 2020; Röder et al. 2020). This additional income could enable households to afford foods that they previously could not, allowing for greater diversity within diets (Kline et al. 2017; SEI 2020).

It is important to note that several studies have identified that policies to expand the bioeconomy, of which bioenergy is a significant component, have the greatest impact when they are directed at supporting and ensuring the equity of smallholder farmers, rather than large agricultural productions (Sakai et al. 2020). It goes without saying that any change in land use or designation of crops or their residues for different purposes, could have undesired impacts on food security and nutrition, for example the reduced use of residues for soil management (e.g. mulching, biofertiliser) could have impacts on soil quality – see Section 3.1. Therefore, interventions should be carefully planned in consultation with local communities.



### 3. Links between bioenergy byproducts and nutrition

The second stage along the bioenergy value chain explored in this literature review was bioenergy byproducts; this includes any secondary products from the production of bioenergy. This section specifically reviewed the available research on the role of soil quality on nutrition, and the potential of bioenergy byproducts, such as biochar and digestate, to improve soil quality and nutritional quality of food crops when applied as soil amendment. Links between the application of biochar and digestate as soil amendment and soil quality and fertility depend on several factors, including application regime, soil type, climate, and crop, among others. Although many positive case studies are available, it is difficult to draw universal conclusions. The consequent impacts on nutrition are indirect and inconclusive; this area therefore requires further research.

#### 3.1. Soil Quality

Soil degradation affects nutrition and health through its adverse effects on quantity and quality of food production (Lal 2009). Soil quality refers to the capacity of soil to perform ecosystem functions such as production of biomass and net primary productivity, biodegradation of contaminants, moderation of climate, purification of water, storage of water and plant nutrients, and recycling of elements (Lal 2009). Soil degradation impacts food and nutrition security directly through reduction in crop yield and decline in nutritional value of crops including protein content and micronutrients, as well as indirectly through reduction in efficiency of inputs and additional land area required to compensate for the loss of production (Lal 2009). Additionally, nutrients may be present in the soil, but they may not be available to plants, which in turn reduces nutrient intake by consumers, a concept called hidden hunger (Pozza & Field 2020; White & Brown 2010). Without secure soil quality, nutritious food will become harder to produce. It is therefore imperative to obtain soil security if nutrition security is desired.

#### 3.2. Biochar and Digestate

If soil is unable to support production of food, human intervention will be required, for example through the addition of fertilizer. Chemical fertilizers have been widely used to achieve enhanced productivity in global agricultural systems, however byproducts of bioenergy such as biochar and digestate provide an additional option for soil amendment. It should be noted that, while some studies suggest that biochar and digestate can replace chemical fertilizer all together (Koszel & Lorencowicz 2020), whether the addition of biochar or digestate over chemical fertilizer significantly improves the nutritional content of crops is unclear.

Studies *have* shown that the addition of biochar to soil can have a positive impact on soil health, such as enhancing chemical and physical properties of soil, promoting biological functioning of soil, and detoxifying soil contaminants. A case study conducted by Kumar et al. (2017) explored the influence of various biochars on crop yield and disease resistance of *Capiscum annuum* L., or the sweet pepper. The study found that soil that had been applied with biochar had significant positive effects on fruit yield and quality, as well as on resistance against the pathogen that causes

powdery mildew. The study did conclude, however, that these improvements were not directly related to increased soil nutrients or changes in plant nutritional status, rather due to influences on the rhizosphere/pathogen/microbiome plant system through the addition of biochar to the soil. A study conducted by Vijay et al. (2021) sought to explore the impact of biochar application on soil health, crop productivity, and its potential role in carbon sequestration. The study showed that biochar application provided greater benefits in improving soil health and crop yields in degraded tropical soils. However, the authors acknowledged that the number of biochar field studies are lacking in comparison to small-scale studies conducted in labs or greenhouses, and it is therefore an area that requires further exploration.

A case study from Ghana explores the potential positive impacts of biochar deployment in the case where forestry and agro-waste are converted into pellets that can be used as a replacement for woodfuel in gasifier cookstoves, reducing pressure on forest ecosystems. The biochar has the potential to restore soil polluted by heavy metals, increase soil water-holding capacity, and increase the concentration of valuable plant nutrients such as calcium, nitrogen, and phosphorus (GBEP, 2020).

Results of studies exploring the effects of biogas digestate (or bioslurry) on soil quality are ambiguous and depend upon input biomass, soil type and application regime. The effect of the use of digestate as biofertilizer has been found to be in general positive compared with the use of untreated crops in relation to biological stability of relevant nutrient compounds and phytotoxicity of specific biomass (Paolini et al. 2018). However, the direct impacts on soil fertility from digestate application are believed to be of low relevance in the long term, whilst the greatest impact on soil fertility is expected from consequent changes in cropping systems driven by the introduction of an anaerobic digester, such as changed harvesting times, removal of crop residues or crop rotations with new energy crops (Möller, 2015).

A report by FAO in 2013 synthesized various case studies comparing the impacts on crop yield of bioslurry application versus other organic fertilizers, synthetic fertilizers, and non-fertilizers. Results for each study varied, based on type of crop. One study compared wheat yield after bioslurry application to no fertilizer use and found that the bioslurry-treated sample performed better than the sample without any fertilizer. Another study, which compared Kohlrabi yield after bioslurry application to synthetic fertilizer application, found that Kohlrabi yields were identical. The FAO report yielded similar conclusions to the studies presented in this literature review – that the effects of the use of biogas digestate on soil quality and crop yield are promising, but largely inconclusive and require more exploration.

## 4. Links between modern bioenergy use and nutrition

The third stage along the bioenergy value chain that was explored in this literature review was bioenergy use. This section reviewed the available literature on the use of bioenergy in improved cookstoves and the cold chain, and how nutrition may be impacted. From the available literature, it appears that the use of modern bioenergy for cooking and for refrigerated food transport and storage has positive but indirect impacts on nutrition. However, further research to determine the strength of these linkages could be beneficial.

### *4.1. Indoor Air Quality, Improved Cookstoves and other clean cooking solutions*

Over 2.5 million people worldwide, primarily in developing countries, are still reliant on traditional bioenergy to fulfil energy demands, relying solely on open and inefficient fires to fulfil cooking and heating needs. The situation is particularly acute in Sub-Saharan Africa, where over 80 percent of the population lack modern energy access (IEA n.d.). Transitioning from traditional biomass cookstoves to improved cookstoves (ICS) or other clean cooking solutions, such as biogas or ethanol stoves, can have several positive impacts, including on indoor air pollution, hygiene, and cooking efficiency.

Improved cookstoves – more fuel-efficient biomass stoves with intended toxic gas emission reductions – have been found to significantly reduce concentrations of PM<sub>2.5</sub>, carbon monoxide (CO), and black carbon from inside of households, resulting in decreases in lower respiratory infections, as well as other health issues such as headaches and eye irritation (Singh et al. 2012). Some studies have pointed out that these reductions in emissions are still result in levels much higher than those recommended by the World Health Organization (annual target of 10 µg/m<sup>3</sup> for PM<sub>2.5</sub> and an interim target of 35µg/m<sup>3</sup> that stoves need to meet to reduce lower respiratory infections), but nonetheless, they remain a significant improvement (Stanistreet et al. 2021). In Kenya, a pilot project to improve biomass use efficiency through the adoption of biochar producing gasifier stoves, examined the energy use efficiency, concentrations of indoor air pollutants in the air during cooking, and biochar production rates and found significant reductions in indoor smoke and improvements in efficiency (GBEP, 2020). In addition to improving indoor air quality, users from a case study on ICS in Nepal recognized improved cleanliness of the kitchen and kitchen utensils after switching (Singh et al. 2012). A study conducted by Suresh et al. (2016) studied the performance of different types of ICS (two natural draft and one forced draft) in comparison to the traditional cookstove. The study found that there was no significant difference in indoor concentrations of PM<sub>2.5</sub> and CO when natural draft and traditional cookstoves were used, but significantly lower concentrations of PM<sub>2.5</sub> and CO were recorded when using the forced draft cookstove. Additionally, all three ICS showed reduced cooking times and a reduction in the amount of fuel required to cook. These findings may align with the main hypothesis of the Anderman et al. (2015) study on biogas cookstoves (see below), in which households with improved cookstoves will be able to have greater diet diversity, regardless of whether their cookstoves are solid biomass or biogas.

As well as ICS, bioenergy also offers opportunities for other clean cooking solutions, such as cookstoves using biogas or ethanol. A case study from Southern India showed that not only do

biogas cookstoves improve indoor air pollution, but they also increase cooking efficiency and reduce overall cook times (Anderman et al. 2015). Because biogas cookstoves are more efficient than traditional cookstoves, households with biogas cookstoves may have more diverse diets as compared to households with traditional cookstoves. This is because cooks have more control over temperature and cooking time with alternative stoves, so they may choose to add different items to their meals that were previously too time consuming or posed too high a spoilage risk because of uncontrollable stove temperatures (Anderman et al. 2015).

Ethanol cookstoves can also offer a viable clean cooking solution that may improve nutrition security through improved health. They have been shown to improve pregnancy outcomes of users compared to traditional stoves in randomized-controlled trials (Alexander et al. 2018). Furthermore, in experiments in three localities in Ethiopia, ethanol cookstoves reduced average PM<sub>2.5</sub> concentrations by 84 percent and average CO concentrations by 76 percent compared with traditional biomass cookstoves (Pennise et al. 2009). Ethanol stoves have also been shown to have improved health outcomes compared to kerosene alternatives, with lower emissions of carbon soot and greenhouse gases (Dioha et al. 2012).

While ICS have been predicted to improve cooking efficiency and indoor air quality, not all households are able to acquire them due to high upfront costs or cost and availability of fuel, and must still rely on traditional biomass cookstoves (Stanistreet et al. 2021).

#### ***4.2. Food storage and transport***

Chilling harvested crops and other produce is integral to preventing spoiling and allowing farmers access to local, national, and international markets for their agricultural outputs. However, lack of access to reliable grid electricity in rural areas has hindered the development of conventional cold storage technologies. As a clean energy source, biogas provides a sustainable alternative to meeting global agricultural demand by extending the shelf life of produce through refrigerated storage (USAID 2020). Typically, solar energy is the clean energy source used in cold storage, but biogas-powered refrigeration also presents an opportunity to introduce new cold storage technologies.

The potential use of biogas to power milk refrigeration has become appealing because it capitalizes on a readily-available waste stream – cow manure – for power (USAID 2020). A case study for biogas power generation from dairy cattle in Kenya, which aimed to determine the profitability of biogas, found that the upfront capital costs of biogas-powered refrigeration are quite high but that both overall financial and economic returns were positive. The study also found that it had positive impacts on soil quality, indoor air pollution, fertilizer use and efficiency, food loss, GHG emissions and access to energy (FAO 2018). However, research of the potential use of biogas technologies in the cold chain is still lacking and requires more in-depth exploration to determine its feasibility and impact on preservation of food in different contexts.

## 5. Conclusions

As pressure on global agricultural systems increases due to rapidly growing populations and climate change, nutrition security and the ability to ensure and maintain healthy diets is threatened. This literature review sought to identify, using the available literature, the links between bioenergy and nutrition, and the ways in which bioenergy can be deployed to improve global nutrition.

The production and use of bioenergy as part of integrated, sustainable production systems, offers potential to aid in the maintenance and enhancement of nutrition security. Bioenergy production and its byproducts offer the opportunity to facilitate nutrition security by improving soil quality through mechanisms such as multiple cropping systems, phytoremediation, and the use of biochar and digestate as soil amendment. Biomass production for bioenergy additionally presents an opportunity to diversify income, particularly of rural and smallholder farmers. Modern bioenergy use can also improve cooking systems by replacing traditional cookstoves, thereby reducing indoor air pollution and improving kitchen hygiene. The use of bioenergy for cold chains and food storage can reduce spoilage and waste, thus ensuring food safety to sustain life and promote good health, and improving the access of rural populations to more diverse markets.

The findings from the articles reviewed evidence of **multiple indirect or implied linkages between bioenergy and nutrition**. That is to say that, although there is potential that bioenergy can indirectly work to improve nutrition and achieve and promote healthy diets, the current available research in this area is lacking and requires more exploration. The bioenergy and nutrition nexus provides great opportunity for future research, to better determine the role of bioenergy in nutrition. Future research could highlight and compile examples of the good practices within bioenergy production that help to safeguard or ensure nutrition security.

## 6. APPENDIX: List of articles cited in the literature review exploring the nexus between bioenergy and nutrition

Article Citation	Article Focus	Outcome of Interest
Alexander, D.A. et al. 2018. Pregnancy outcomes and ethanol cook stove intervention: A randomized-controlled trial in Ibadan, Nigeria. <i>Environment International</i> , 111. <a href="https://doi.org/10.1016/j.envint.2017.11.021">https://doi.org/10.1016/j.envint.2017.11.021</a>	A study conducted in Ibadan, Nigeria to determine the impact of cooking with ethanol on pregnancy outcomes	Pregnancy outcomes
Anderman, T.L. et al. 2015. Biogas cook stoves for healthy and sustainable diets? A case study in Southern India. <i>Frontiers in Nutrition</i> , 2(28). <a href="http://dx.doi.org/10.3389/fnut.2015.00028">http://dx.doi.org/10.3389/fnut.2015.00028</a>	Improved indoor air quality because of switching from traditional cookstoves to biogas cookstoves. Also details the impact of biogas cookstoves on the female head of house	Indoor air pollution and improved diet diversity
Beattie, S. & Sallu, S.M. 2021. How does nutrition climate-smart agriculture policy in Southern Africa? A systemic policy review. <i>MDPI Sustainability</i> , 13. <a href="https://doi.org/10.3390/su13052785">https://doi.org/10.3390/su13052785</a>	Role of climate-smart agriculture in food and nutrition security policies in Southern Africa	Climate-smart agriculture
Campbell, J.E., Lobell, D.B., Genova, R.C., & Field, C.B. 2008. The global potential of bioenergy on abandoned agriculture lands. <i>Environmental Science and Technology</i> , 42(15). <a href="https://doi.org/10.1021/es800052w">https://doi.org/10.1021/es800052w</a>	An exploration of the potential to harvest energy crops on marginal or degraded lands	Bioenergy crop production on degraded or marginal lands
Dioha, I.J., Ikeme, C.H., Tijjani, N., & Dioha, E.C. 2012. Comparative studies of ethanol and kerosene fuels and cook stoves performance. <i>Journal of Natural Sciences Research</i> , 2(6). <a href="http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.856.754&amp;rep=rep1&amp;type=pdf">http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.856.754&amp;rep=rep1&amp;type=pdf</a>	Comparative studies of ethanol and kerosene fuels and their performance with household kerosene cookstoves of the same dimensions and geometry were carried out. The authors examined the different sources of domestic cooking fuels such as LPG, kerosene, fuel wood, and ethanol.	Cooking efficiency of ethanol and kerosene stoves

Emmerling, C., Schmidt, A., Ruf, T., Von Francken-Welz, H., & Thielen, S. 2017. Impact of newly introduced perennial bioenergy crops on soil quality parameters at three different locations in W-Germany. <i>Journal of Plant Nutrition and Soil Science</i> , 180(6). <a href="https://doi.org/10.1002/jpln.201700162">https://doi.org/10.1002/jpln.201700162</a>	An analysis of the impacts of perennial energy crops such as <i>Miscanthus</i> , switchgrass and reed canary grass, and the newly introduced cup plant, giant knotweed, tall wheatgrass, virginia mallow, and wild plant mixtures have on the soil organic carbon and nitrogen pools, microbial properties, and earthworm activity at three different study sites in W-Germany with varying soil conditions after an experimental period of five years.	Bioenergy crops and soil quality
Faße, A., Winter, E., & Grote, U. 2014. Bioenergy and rural development: The role of agroforestry in a Tanzanian village economy. <i>Ecological Economics</i> , 106. <a href="https://doi.org/10.1016/j.ecolecon.2014.07.018">https://doi.org/10.1016/j.ecolecon.2014.07.018</a>	Analysis of the role of bioenergy crops such as <i>Jatropha curcas</i> , cassava, and sugarcane on increasing market access and income diversification strategies in rural Tanzania	Agroforestry; rural development
FAO. 2018. <i>Costs and Benefits of Clean Energy Technologies in the Milk, Vegetable, and Rice Value Chains</i> . Rome, Italy.	Analysis of three food supply value chains and the role of various clean energy technologies. The use of biogas in the milk supply value chain was examined .	Cold storage
FAO. 2012. The Impact of Climate Change and Bioenergy on Nutrition. <a href="https://doi.org/10.1007/978-94-007-0110-6">https://doi.org/10.1007/978-94-007-0110-6</a>	A detailed overview on how climate change and bioenergy impact nutrition. Report examines both the positive and negative impacts of bioenergy	Nutrition
FAO. 2013. <i>Bioslurry = Brown Gold? A review of scientific literature on the co-product of biogas production</i> . Rome, Italy. <a href="https://www.fao.org/3/i3441e/i3441e.pdf">https://www.fao.org/3/i3441e/i3441e.pdf</a>	A synthesis of peer-reviewed scientific literature on the role of bioslurry as fertilizer	Soil quality; crop yield
GBEP. 2020. <i>Working Group on Capacity Building. Activity Group 4: Towards Sustainable Modern Wood Energy Development</i> .	An exploration of a variety of case studies exploring biochar application on crop yield, forest landscape exploration,	Biochar application; crop yield; indoor air quality; energy

<a href="http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/AG4/AG4_Collection_of_examples_links_sust._wood_energy_and_FLR_June2020.pdf">http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/AG4/AG4_Collection_of_examples_links_sust._wood_energy_and_FLR_June2020.pdf</a>	soil quality, and indoor air pollution	efficiency; forest landscape restoration
Geng et. al. 2017. Bioenergy production on marginal land in Canada: Potential, economic feasibility, and greenhouse gas emissions impacts. <i>Applied Energy</i> , 205. <a href="http://dx.doi.org/10.1016/j.apenergy.2017.07.126">http://dx.doi.org/10.1016/j.apenergy.2017.07.126</a>	A study identifying the productivity, economic feasibility and greenhouse gas emissions impact on using marginal land for bioenergy production in Canada	Bioenergy production on marginal lands; sustainable development
Gomes, H.I. 2012. Phytoremediation for bioenergy: Challenges and opportunities. <i>Environmental Technology Reviews</i> , 1(1). <a href="http://dx.doi.org/10.1080/09593330.2012.696715">http://dx.doi.org/10.1080/09593330.2012.696715</a>	Biomass produced in phytoremediation can represent an important environmental co-benefit, by improving soil quality and functionality	Phytoremediation co-benefits
Hejna, M., Onelli, E., Moscatelli, A., Bellotto, M., Cristiani, C., Stroppa, N., & Rossi, L. 2021. Heavy-Metal Phytoremediation from Livestock Wastewater and Exploitation of Exhausted Biomass. <i>International Journal of Environmental Research and Public Health</i> , 18(5). <a href="https://doi.org/10.3390/ijerph18052239">https://doi.org/10.3390/ijerph18052239</a>	Phytoremediation to reduce wastewater pollution from livestock production	Phytoremediation ; agricultural wastewater
IEA. n.d. <i>SDG 7 Data and Projections: Access to clean cooking</i> . <a href="https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking">https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking</a>	Data from the IEA, showcasing the use of bioenergy to increase global access to clean cooking	Cooking efficiency
International Advisory Council on Global Economy. 2020. <i>Global Bioeconomy Summit 2020. Expanding the Sustainable Bioeconomy - Vision and Way Forward. Communiqué of the Global Bioeconomy Summit 2020</i> . Berlin, Germany. <a href="https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf">https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf</a>	Exploring the ways in which the bioeconomy can be strengthened through various policies such as capitalizing on the power of science and technology, bioeconomy jobs through partnerships and innovation, mobilizing finance for bioeconomy development, and more	Sustainable development; bioeconomy
IRENA, IEA Bioenergy, FAO. 2017. <i>Bioenergy for Sustainable Development</i> . <a href="https://www.ieabioenergy.com/wp-content/uploads/2017/01/BIOENERGY-">https://www.ieabioenergy.com/wp-content/uploads/2017/01/BIOENERGY-</a>	Global assessments by REN 21, IEA and IRENA find that bioenergy accounts for three-quarters of all renewable energy use today and half of	Sustainable development; bioeconomy;



AND-SUSTAINABLE-DEVELOPMENT-final-20170215.pdf	the most cost-effective options for doubling renewable energy use by 2030. Bioenergy is part of a larger bioeconomy, including agriculture, forestry, and manufacturing	sustainable agriculture
Jung, H.G. 2010. <i>Alfalfa: A Companion Crop with Corn</i> . Proceedings of the Alfalfa/Corn Rotations for Sustainable Cellulosic Biofuels Production, June 29-30, 2010, Johnston, Iowa.: <a href="http://www.alfalfa.org/2010WS/Jung.pdf">http://www.alfalfa.org/2010WS/Jung.pdf</a> .	Study analyzing the incorporation of alfalfa into rotation with corn offers an opportunity to maintain biofuel production and alleviate the negative impacts related to continuous corn production. Study also explores how this crop rotation would fulfill the food and feed needs for starch and protein traditionally provided by the corn/soybean production system of the American Midwest	Sustainable development; biofuel production
Karanja, A. & Gasparatos, A. 2019. Adoption and impacts of clean bioenergy cookstoves in Kenya. <i>Renewable and Sustainable Energy Reviews</i> , 102. <a href="https://doi.org/10.1016/j.rser.2018.12.006">https://doi.org/10.1016/j.rser.2018.12.006</a>	Comprehensive review of the knowledge about the context, status, adoption, and impacts of clean bioenergy stoves in Kenya and suggestions for an effective transition towards universal clean cookstoves	Improved cookstoves
Kline et al. 2021. Reconciling food security and bioenergy: Priorities for action. <i>Global Change Biology Bioenergy</i> , 9. <a href="https://doi.org/10.1111/gcbb.12366">https://doi.org/10.1111/gcbb.12366</a>	An examination of the complex interactions among food security, bioenergy sustainability, and resource management. Explores the various ways in which bioenergy can have positive impacts on daily life, including through crop and income diversification	Food security
Koszel, M. & Lorencowicz, E. 2020. Agricultural use of biogas digestate as a replacement fertilizer. <i>Agriculture and Agricultural Science Procedia</i> , 15.	Explores how the use agricultural biogas digestate can act as a replacement for non-organic fertilizers	Digestate as a replacement for chemical fertilizer

<a href="https://doi.org/10.1016/j.aaspro.2015.12.004">https://doi.org/10.1016/j.aaspro.2015.12.004</a>	typically used in agricultural production.	
Kumar, A. et al. 2017. Biochar potential in intensive cultivation of <i>Capsicum annuum</i> L. (sweet pepper): Crop yield and plant protection. <i>Journal of the Science of Food and Agriculture</i> , 98. <a href="https://doi.org/10.1002/jsfa.8486">https://doi.org/10.1002/jsfa.8486</a>	The influence of various biochars on crop yields and disease resistance of <i>Capsicum annuum</i> L (sweet pepper)	Biochar and crop yield
Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. <i>Food Security</i> , 1. <a href="https://doi.org/10.1007/s12571-009-0009-z">https://doi.org/10.1007/s12571-009-0009-z</a>	Explores how degraded soil negatively affects human nutrition through its adverse impacts on quantity and quality of food production. Suggests strategies for combatting soil degradation such as enhancing soil fertility and micronutrient availability	Soil security and nutrition
Ma, Y., Fu, S., Zhang, X., Zhao, K., & Chen, H.Y.H. 2017. Intercropping improves soil nutrient availability, soil enzyme activity and tea quantity and quality. <i>Applied Soil Ecology</i> , 119. <a href="https://doi.org/10.1016/j.apsoil.2017.06.028">https://doi.org/10.1016/j.apsoil.2017.06.028</a>	An examination of how intercropping chestnut trees in a tea plantation effects the seasonal dynamics of soil nutrients, soil enzyme activities, and tea quantity and quality in a temperate region in China	Intercropping and soil quality
Makumba, W., Janssen, B., Oenema, O., Akinnifesi, F.K., Mweta, D., Kwesiga, F. 2006. The long-term effects of a gliricidia–maize intercropping system in Southern Malawi, on gliricidia and maize yields, and soil properties. <i>Agriculture, Ecosystems, &amp; Environemt</i> , 116(1-2). <a href="https://doi.org/10.1016/j.agee.2006.03.012">https://doi.org/10.1016/j.agee.2006.03.012</a>	An analysis of a gliricidia–maize simultaneous intercropping agroforestry system for soil fertility improvement and yield increase in highly populated areas of sub-Saharan Africa where landholding sizes are very small and inorganic fertilizer use is very low	Intercropping; soil quality
Möller, K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. <i>Agronomy for Sustainable Development</i> , 35. <a href="https://doi.org/10.1007/s13593-015-0284-3">https://doi.org/10.1007/s13593-015-0284-3</a>	This review discusses the current state of knowledge on the effects of anaerobic digestion on organic compounds in digestates and the most important processes influencing N emissions in the field, as well as the	Soil quality; biological activity

	possible long-term effects on soil microbial biomass and soil fertility.	
Nabel, M., Schrey, S.D., Temperton, V.M., Harrison, L., & Jablonowski, N.D. 2018. Legume intercropping with bioenergy crop <i>Sida hermaphrodita</i> on marginal soil. <i>Frontiers in Plant Science</i> , 2. <a href="https://doi.org/10.3389/fpls.2018.00905">https://doi.org/10.3389/fpls.2018.00905</a>	Analysis of <i>Sida hermaphrodita</i> as a promising species to be cultivated in an extensive cropping system on marginal soils in combination with organic fertilization using biogas digestates	Intercropping with bioenergy crops; marginal land improvements
Pandey, V.C., Bajpai, O., & Singh, N. 2016. Energy crops in sustainable phytoremediation. <i>Renewable and Sustainable Energy Reviews</i> , 54. <a href="https://doi.org/10.1016/j.rser.2015.09.078">https://doi.org/10.1016/j.rser.2015.09.078</a>	Exploration of how four energy crops – <i>Miscanthus</i> , <i>Ricinus</i> , <i>Jatropha</i> , and <i>Populus</i> – can be used in large scale to remediate contaminated land	Phytoremediation using bioenergy crops
Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., & Cecinato, A. 2018. Environmental impact of biogas: A short review of current knowledge. <i>Journal of Environmental Science and Health</i> , 53(10). <a href="https://doi.org/10.1080/10934529.2018.1459076">https://doi.org/10.1080/10934529.2018.1459076</a>	In this study, the current knowledge about the impact of biogas technology is presented and discussed. The survey reports the emission rate estimates of the main greenhouse gases (GHG), namely CO <sub>2</sub> , CH <sub>4</sub> and N <sub>2</sub> O, according to several case studies conducted over the world	Sustainable development; climate change; environmental implications of biogas
Pennise, D. et al. 2009. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. <i>Energy for Sustainable Development</i> , 13(2). <a href="https://doi.org/10.1016/j.esd.2009.04.003">https://doi.org/10.1016/j.esd.2009.04.003</a>	This study was undertaken to assess the potential of two types of improved cookstoves to reduce indoor air pollution in African homes. An ethanol stove, the CleanCook, was tested in three locations in Ethiopia: the city of Addis Ababa and the Bonga and Kebribeyah Refugee Camps, while a wood-burning rocket stove, the Gyapa, was evaluated in Accra, Ghana	Indoor air quality; improved biomass cookstoves
Pozza, L.E. & Field, D.J. 2020. The science of soil security and food security. <i>Soil Security</i> , 1.	Examines the relationship between soil security and food security, especially as	Soil security and food security

<a href="https://doi.org/10.1016/j.soisec.2020.100002">https://doi.org/10.1016/j.soisec.2020.100002</a>	global population growth accelerates, placing greater demand on the agricultural system. Four potential solutions were discussed	
Röder, M., Mohr, A., Liu, Y. 2020. Sustainable bioenergy solutions to enable development in low-and middle-income countries beyond technology and energy access. <i>Biomass and Bioenergy</i> , 143. <a href="https://doi.org/10.1016/j.biombioe.2020.105876">https://doi.org/10.1016/j.biombioe.2020.105876</a>	A synthesis of the key findings from 15 research articles published in the Special Issue “Development of modern bioenergy approaches in low- and middle-income countries,” published in the Journal of Biomass & Bioenergy. Shows how the contribution of modern bioenergy systems can have environmental, economic, and social co-benefits	Rural development; income diversification
Rogers, J.N., Stokes, B., Dunn, J., Cai, H., Wu, M., Haq, Z., & Baumes, H. 2016. An assessment of the potential products and economic and environmental impacts resulting from a billion-ton bioeconomy. <i>Biofuels, Byproducts, &amp; Biorefining</i> , 11(1). <a href="https://doi.org/10.1002/bbb.1728">https://doi.org/10.1002/bbb.1728</a>	A summation of several analyses to assess the size and benefits of a Billion Ton Bioeconomy, a vision to enable a sustainable market for producing and converting a billion tons of US biomass to bio-based energy, fuels, and products by 2030. Impacts include income diversification for rural communities	Sustainable development; income diversification
Rowe, R.L., Street, N.R., Taylor, G. 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. <i>Renewable and Sustainable Energy Reviews</i> , 13(1). <a href="https://doi.org/10.1016/j.rser.2007.07.008">https://doi.org/10.1016/j.rser.2007.07.008</a>	This review assesses the evidence for potential impacts of large-scale bioenergy crop deployment primarily within the UK context, but with wider implications for Europe, the United States, and elsewhere. The review focused on second generation lignocellulosic crops, primarily grown for food.	Sustainable development; bioenergy crop production
Sakai, P. et al. 2020. Understanding the implications of alternative bioenergy crops to support smallholder farmers in	Bioenergy production and consumption can help sustain smallholder farmers’ energy	Rural development;

Brazil. <i>MDPI Sustainability</i> , 12. <a href="http://dx.doi.org/10.3390/su12052146">http://dx.doi.org/10.3390/su12052146</a>	needs, as well as generate employment and income. Study explores how three crops in Brazil – sugarcane, landrace maize, and sweet potato - can support smallholder farmers' development in an equitable way	income diversification
Shortall, O.K. 2013. "Marginal land" for energy crops: Exploring definitions and embedded assumptions. <i>Energy Policy</i> , 62. <a href="https://doi.org/10.1016/j.enpol.2013.07.048">https://doi.org/10.1016/j.enpol.2013.07.048</a>	An analysis of how the definitions of "marginal land" impact which parcels of land are able to be used for bioenergy crop harvest	Marginal land; bioenergy crop production
Singh, A., Tuladhar, B., Bajracharya, K., & Pillarisetti, A. 2012. Assessment of effectiveness of improved cook stoves in reducing indoor air pollution and improving health in Nepal. <i>Energy for Sustainable Development</i> , 16(4). <a href="https://doi.org/10.1016/j.esd.2012.09.004">https://doi.org/10.1016/j.esd.2012.09.004</a>	A case study assessing the impact of improved cookstoves in reducing indoor air pollution in Nepal. The study specifically looked at concentrations of particulate matter 2.5 and carbon monoxide inside various kitchens, before and after the installation of improved cookstoves	Indoor air quality; improved cookstoves
Singh, S.R. et al. 2021. Intercropping in Sugarcane Improves Functional Diversity, Soil Quality and Crop Productivity. <i>Sugar Tech</i> , 23. <a href="https://doi.org/10.1007/s12355-021-00955-x">https://doi.org/10.1007/s12355-021-00955-x</a>	A study comparing intercropping with sugarcane to traditional non-intercropping on soil quality, crop yield, and functional diversity	Intercropping; crop yield; soil quality
Smith, K.R., Dutta, K., Chengappa, C., Gusain, P.P.S., Masera, O., Berrueta, V., Edwards, R., Bailis, R., & Shields, K.N. 2007. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: Conclusions from the Household energy and Health Project. <i>Energy for Sustainable Development</i> , 11(2). <a href="https://doi.org/10.1016/S0973-0826(08)60396-8">https://doi.org/10.1016/S0973-0826(08)60396-8</a>	Monitoring and evaluation of changes in indoor air quality and stove fuel performances in India and Mexico. Results for stove performance were mixed, but results for indoor air quality showed significant improvements over a 48-hour period	Biomass cookstoves; indoor air quality; cooking efficiency

<p>Stainstreet, D. et al. 2021. Which biomass stove(s) capable of reducing household air pollution are available to the poorest communities globally? <i>International Journal of Environmental Research and Public Health</i>, 18. <a href="https://doi.org/10.3390/ijerph18179226">https://doi.org/10.3390/ijerph18179226</a></p>	<p>In-depth exploration on which improved cookstoves are available to the world's poorest and rural communities. The authors found that the cheapest stoves do not have a significant impact on indoor air quality, and provided recommendations for how to better incorporate improved cookstoves</p>	<p>Biomass cookstoves; indoor air pollution</p>
<p>Stockholm Environment Institute. 2020. <i>Emerging bioeconomy opportunities in Africa</i>. <a href="https://cdn.sei.org/wp-content/uploads/2021/02/201120b-mash-diaz-chavez-croton-tree-case-study-report-2010i.pdf">https://cdn.sei.org/wp-content/uploads/2021/02/201120b-mash-diaz-chavez-croton-tree-case-study-report-2010i.pdf</a></p>	<p>A case study on the impact of the bioeconomy in communities across Africa. Highlights how a more developed bioeconomy can lead to additional income for farmers and others</p>	<p>Rural development; income diversification</p>
<p>Suresh, R., Singh, V.K., Malik, J.K., Datta, A., &amp; Pal, R.C. 2016. Evaluation of the performance of improved biomass cooking stoves with different solid biomass fuel types. <i>Biomass and Bioenergy</i>, 95. <a href="https://doi.org/10.1016/j.biombioe.2016.08.002">https://doi.org/10.1016/j.biombioe.2016.08.002</a></p>	<p>Biogas stoves are not the only option for improved indoor cookstoves. This paper is an exploration of the performance of different types of solid biomass cookstoves, comparing two natural draft stoves and one forced draft to the traditional cookstove</p>	<p>Biomass cookstoves; cooking efficiency</p>
<p>USAID. 2020. <i>Powering Agriculture: An Energy Grand Challenge for Development. Technology Case Study: Clean Energy Cold Storage</i>. Washington, DC. <a href="https://pdf.usaid.gov/pdf_docs/PA00WHC6.pdf">https://pdf.usaid.gov/pdf_docs/PA00WHC6.pdf</a></p>	<p>Report prepared by the United States Agency for International Development on the role of clean energy technologies on the cold chain. The report identified two biogas case studies – SimGas and Thermogenn – both of which are used for the cooling and storage of milk and other dairy products</p>	<p>Cold storage</p>
<p>Vijay, V. et al. 2020. Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. <i>Frontiers in</i></p>	<p>In-field study that explored the impact of biochar on soil health (soil's physical, chemical, and biological</p>	<p>Biochar; soil quality; crop yield</p>

<i>Energy Research</i> , 9. <a href="https://doi.org/10.3389/fenrg.2021.710766">https://doi.org/10.3389/fenrg.2021.710766</a>	properties), crop yield, and its potential role in carbon sequestration	
Volk, T.A., Abrahamson, L.P., Nowak, C.A., Smart, L.B., Tharakan, P.J., White, E.H. 2006. The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. <i>Biomass and Bioenergy</i> , 30. <a href="https://doi.org/10.1016/j.biombioe.2006.03.001">https://doi.org/10.1016/j.biombioe.2006.03.001</a>	A case study on the use of the willow ( <i>Salix</i> spp.) in the northeastern United States for bioenergy and bioproducts. The study examines the ways in which willow can be deployed for other applications, such as phytoremediation, across the northeastern United States	Phytoremediation
White, P.J., & Brown, P.H. 2010. Plant nutrition for sustainable development and global health. <i>Annals of Botany</i> , 105. <a href="https://doi.org/10.1093/aob/mcq085">https://doi.org/10.1093/aob/mcq085</a>	An analysis of the mineral elements required for plant nutrition and how crop production is often limited by low phytoavailability of these minerals. The authors also explore how the lack of these minerals impacts human nutrition and food security	Sustainable development; crop yield
Yan, A., Wang, Y., Tan, S.N., Yusof, M.L.M., Ghosh, S., Chen, Z. 2020. Phytoremediation: A Promising approach for revegetation of heavy-metal polluted land. <i>Frontiers in Plant Science</i> , 11. <a href="https://doi.org/10.3389/fpls.2020.00359">https://doi.org/10.3389/fpls.2020.00359</a>	An analysis on the potential of phytoremediation as an eco-friendly approach to revegetate heavy metal-polluted soils in a cost-effective manner	Phytoremediation ; revegetation





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