Bioenergy and nutrition: Positive linkages for the achievement of the UN Sustainable Development Goals

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Bioenergy and nutrition: Positive linkages for the achievement of the UN Sustainable Development Goals

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Abstract

Bioenergy and nutrition represent two key elements in maintaining health and well-being. Bioenergy is a form of renewable energy produced from organic materials, which can be used for generating power, while nutrition, on the other hand, is related to the ability of food to provide the proper nutrients to living beings and the factors that make up a healthy diet. The 2030 Sustainable Development Agenda has brought considerable attention to the importance of food security and nutrition, particularly under SDG2, while concurrently highlighting the need to ensure affordable, reliable, sustainable, and modern energy access for all under SDG7. The accomplishment of these two Goals is crucial for almost all others, as they are closely interconnected with many cross-cutting elements and commonly framed in the Water Energy Food Nexus. In this context, modern bioenergy has the potential to aid in the accomplishment of the SDGs, when value chains and conversion processes are designed and managed in an appropriate and sustainable manner. Nevertheless, the positive relationship between bioenergy and nutrition is an overlooked nexus, whose analysis has been too often limited to the competition for resources, such as land, water, energy, and other inputs. Considering this, the present review was developed for both the nutrition and bioenergy communities to begin to overcome the limits of the food versus fuel paradigm, by analyzing this intricate nexus and bringing to light interlinkages and potential synergies existing between bioenergy and nutrition. So far, such linkages appear indirect or implied, therefore further research in this area would be beneficial. The strongest links between bioenergy and nutrition identified include: greater cooking efficiency, reduced indoor air pollution, and improved environmental sanitation through bioenergy clean cooking solutions; energy access for transporting, storing, and cooking food, thus reducing food loss and

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waste and diversifying diets; improved soil fertility through Carbon Capture and Storage (CCS), phytoremediation, and integrated biomass production systems; and better rural livelihoods and increased income by introducing bioenergy production and use as a circular economy practice. The major significance of this review is the identification of examples of good practices applied along the different stages of the bioenergy value chain with potential co-benefits for nutrition. In this way, this work aims to provide preliminary findings for researchers to better determine the ways in which bioenergy can be deployed to improve global nutrition.

This article is categorized under:
Sustainable Energy > Bioenergy
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bioenergy, food security, nutrition, SDG2, SDG7

1 | INTRODUCTION

The latest available evidence indicates that the global challenge to end hunger and all forms of malnutrition keeps growing: the number of people unable to afford a healthy diet around the world in 2020 increased to almost 3.1 billion, an increase of about 112 million from 2019 (FAO, 2022). This situation reflects the multiple global crises that the world has been recently facing, including the lingering effects of COVID-19 pandemic, rising inflation, the current situation in Ukraine, climate change, macro-economic imbalances, and the shortages of energy, fertilizer, and food.

More than 2.5 million people worldwide, mostly in developing countries, still rely on traditional bioenergy to meet their energy needs, such as cooking and heating using open, ineffective fires. Over 80% of the population in Sub-Saharan Africa lacks access to modern energy, making the situation there particularly acute (IEA, 2022).

Such data are clearly at odds with the Sustainable Development Goals (SDGs) adopted by the United Nations (UN) in 2015 as a global call to action to eradicate poverty, safeguard the environment, and guarantee peace and prosperity for all people by 2030 (United Nations Development Program [UNDP], n.d.). Indeed, food security and adequate nutrition are widely recognized as fundamental human rights and represent two key priorities in the UN 2030 Agenda (United Nations, Department of Economic and Social Affairs, 2015).

Food security refers to the possibility for all people at all times to have both physical and economic access to sufficient, safe and nutritious food that meet dietary needs and food preferences for an active and healthy life; it is defined and understood through its four dimensions: availability, access, stability, and utilization (Food and Agriculture Organization of the United Nations (FAO), 2020). On the other hand, adequate nutrition builds on food security to further ensure access to healthy diets, which include foods that are not just calories but also nutrients, to support health and manage or prevent diseases (United States Agency International Development [USAID], n.d.; United States Department of Agriculture [USDA], n.d.; United Nations, 2015). "Nutrition security" encompasses food security but also goes beyond it, as it includes environmental factors unrelated to food, such as sanitation and health services (Ingram, 2020).

Although the Agenda includes a specific SDG for this paramount theme (i.e., Goal 2 "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" with its accompanying Targets 2.1 and 2.2 [The World Bank, 2020]), all the Goals contain indicators that are highly relevant for improving nutrition security (Scaling up Nutrition, 2015), given the cross-cutting nature of many aspects of the SDGs. For example, better nutrition supports the achievement of Target 3.4 (reducing premature deaths from noncommunicable diseases), and Targets 3.1 and 3.2 (reducing child and maternal mortality; FAO, 2021).

The UN 2030 Agenda, under SDG7, also aims to achieve universal access to affordable, reliable, sustainable, and modern energy services; attain a substantial increase of the share of renewable energy in the global energy mix; and double the global rate of improvement in energy efficiency (United Nations, n.d.). Indeed, access to energy is an essential prerequisite for achieving many other SDGs, as energy facilitates economic development, food security, health and well-being, education, and other related objectives.

In this framework, bioenergy can play a significant role in the sustainable transformation of energy systems (Khatiwada & Purohit, 2021), and contribute to the implementation of the Paris Agreement on climate change, owing to its meaningful greenhouse gas (GHG) mitigation potential (Chum et al., 2011). Indeed, bioenergy could hold several other merits, such as benefiting local and national economies by contributing to agricultural sectors and improving local and global ecology (Li & Khanal, 2016).

Food security, adequate nutrition and bioenergy appear thus evermore closely interrelated, in light of the agronomic models that stand behind bioenergy and bioeconomy value chains; this is especially true in the present context of rapidly growing population, which results in increased pressure on global agricultural systems (Karim, 2013).

However, the current public perception about their interaction is still chiefly negative, on the basis of the deep-rooted conviction that biofuels produced from crops or on cropland compete with food production, increase food prices, and impact soil and water quality (Kline et al., 2016). This view is clearly limited to a narrow concept of bioenergy production that does not embrace the properly-managed and sustainable agricultural practices embedded in modern forms of bioenergy, defined and promoted through directives (e.g., RED-II on low-ILUC risk biofuels), policies, and assessments.

Several studies and book chapters dedicated to this paramount topic have been found in literature, for example: Kline et al. (2016), Sharma et al. (2016), B. Kumar et al. (2009), Matemilola et al. (2019), Tirado et al. (2010), and Popp et al. (2014). These publications mainly focus on how properly-managed bioenergy systems can ensure food security and even improve it, while providing energy security and addressing climate change.

Nevertheless, an active and up-to-date discussion on specific good practices throughout bioenergy value chains that might positively impact nutrition has not yet taken place. Understanding the linkages between nutrition and sustainable bioenergy, as well as the many win-win opportunities to achieve more sustainable agriculture and bioenergy/bioeconomy, is essential to facilitate the achievement of UN SDGs.

Hence, this literature review aims to identify, by collecting and analyzing available evidence, the linkages between nutrition and bioenergy production and use. Although other aspects of food security are not ignored where they could be present, they are not the focus of the research. The review fits in the framework of the collection of positive practices between bioenergy and nutrition developed by the Food and Nutrition Division of the FAO as a contribution to the Global Bioenergy Partnership (GBEP) Programme of Work (GBEP, 2022), with the purpose to acknowledge and leverage this nexus and the opportunities that it generates. An overview of the main contents of this study is shown in Figure 1.

In particular, the study examines the implication and the impacts of bioenergy on agricultural land and soil quality, which influences nutrient content of food, and other aspects of health related to nutrition. In fact, nutritious and quality food can only be produced if soils are healthy, which requires the adoption of long-term sustainable agronomic practices. A healthy living soil is therefore crucial for food security and nutrition (FAO, 2015). However, this study does not specifically target in-depth elements of linkages between soil and food nutrients, nor guidance on healthy diets, but is intended to provide a comprehensive overview of the good practices along the bioenergy value chain—from feedstock production to products and by-product utilization—that could positively affect nutrition, thus contributing to the achievement of the UN SDGs. It is considered that this will be beneficial for a constructive dialogue between practitioners working on both energy and nutrition, to overcome the confining food versus fuel paradigm, and work towards the development of bioenergy solutions that contribute to better nutrition outcomes.

2 | RESULTS

In this section, the main findings of the present review are described. The available literature points towards a few main entry points where modern bioenergy value chains can have positive implications for the improvement of nutrition (see Figure 2).

The analysis builds upon a collection of positive practices between bioenergy and nutrition developed by the Food and Nutrition Division of the FAO, in collaboration with the FAO Office of Climate Change, Biodiversity and Environment, as a contribution to the Global Bioenergy Partnership (GBEP) Programme of Work (GBEP, 2022). The current review updates and further extends this work, whilst also providing a deeper discussion of the consequences and potential follow-up to the review. As a result, this literature review covers 53 studies in total, published between the years of

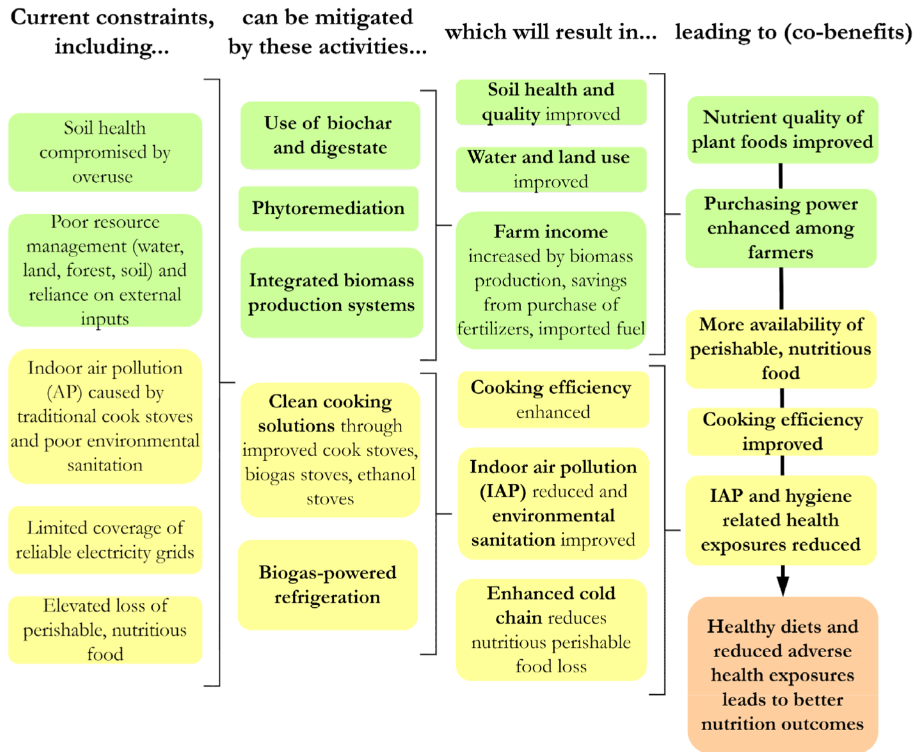

FIGURE 1 Overview of the contents of the present study.

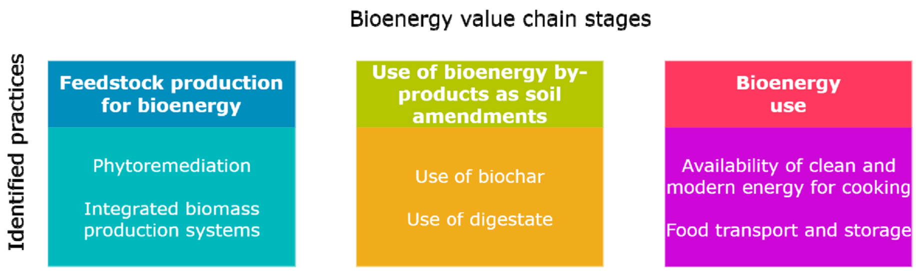

FIGURE 2 Identified practices along bioenergy value chains that might have positive impacts on nutrition.

2006 and 2021, including peer-reviewed papers, technical articles, documents published by nonprofit organizations, and government documents. In addition, this analysis encompasses examples and good practices from case studies at national and local level provided by Partners and Observers of GBEP.

The review is divided into sections based on the stages of a typical bioenergy value chain, that is, (i) feedstock production for bioenergy, (ii) bioenergy use, and (iii) bioenergy by-products. Possible positive linkages between bioenergy and nutrition are discussed at each stage, as seen in the literature, and examples of good practices with potential co-benefits for nutrition are provided where available.

2.1 | Linkages between feedstock production for bioenergy and nutrition

This paragraph explores elements such as sustainable integrated biomass production systems and phytoremediation, which may have a positive impact on soil quality and availability, thus enhancing the potential of the land to produce safe and nutritious food. In addition, indirect impacts on nutrition from income diversification are considered. Figure 3 highlights the key outcomes of the research with regard to this phase of the bioenergy value chain.

2.1.1 | Integrated biomass production systems

Innovative agronomic methods, such as crop rotations and intercropping (e.g., flexible crops and agroforestry) may allow biomass production in agricultural and forestry landscapes simultaneously and sustainably, for a variety of uses (IRENA et al., 2017). In some circumstances, these integrated systems can improve ecosystem services and mitigate the negative effects of land usage, thus enhancing the capacity of the agricultural ecosystem to provide healthy and nutritious food.

Intercropping

Cultivating two or several crop species simultaneously in the same field during a growing season (namely "intercropping") is one such strategy that might lead to an improvement in soil quality (Ofori & Stern, 1987). This method has been used extensively for a long time as it guarantees sustainability and long-term productivity (Ma et al., 2017). In addition, intercropping has a great potential to ensure nitrogen content of soil exhibits (Cong et al., 2014), which is widely recognized as essential and frequently one of the most restricting elements in growth of plants and crop yield; hence its application to soil is essential for ensuring crop production to meet growing agricultural demand. Further evidence points to the possibility that intercropping energy plants like sugarcane can improve soil quality, crop yield, and functional variety (S. R. Singh et al., 2021). Intercropping nitrogen-fixing plants with cash crops can improve soil fertility and reduce soil degradation. For instance, in an example of an agroforestry system, the short-rotation coppicing tree *Gliricidia sepium* could be intercropped with cash crops to reduce soil erosion, while its prunings could be used as green manure to enhance or stabilize the productivity of cash-crops (Makumba et al., 2006; Phiri & Akinnifesi, 2000). Additionally, intercropping reduces the quantity of weeds that consume a large quantity of the soil's nutrients and water, diverting resources from the crops (S. R. Singh et al., 2021). Ma et al. (2017), in a study carried out in a temperate region in China, investigated the effects that intercropping chestnut trees in tea plantations has on a several parameters, for example, seasonal fluctuations of soil nutrients and enzyme activity, as well as tea productivity and quality. The results showed that this practice raised the levels of all the measured soil nutrients, such as nitrogen, potassium, phosphorus, and hydrolysable nitrogen. Moreover, an increase in tea length and weight has been observed, along with the concentration of theanine, amino acid, and catechin, which claimed to be the key compound of green tea accountable for its health benefits, for example, its antioxidant and anti-inflammatory qualities.

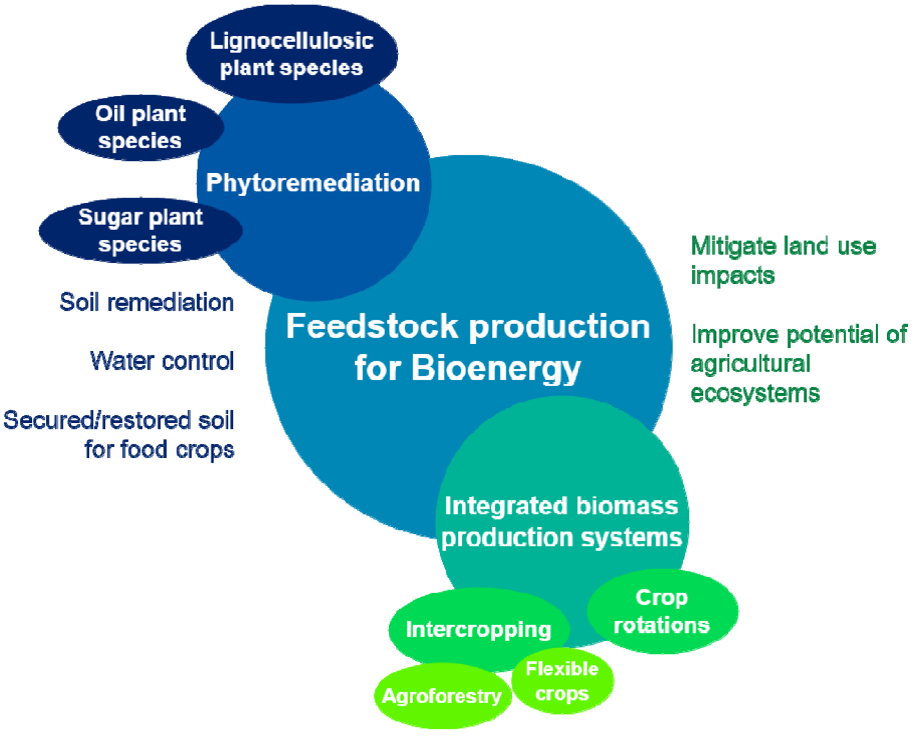

FIGURE 3 Practices to be applied for bioenergy production and related potential positive links with nutrition growing.

Crop rotation

Crop rotation is the process of switching the crops that are cultivated on a certain plot of land from year to year, and represents an essential component of all organic cropping systems as it contributes to healthy soils, pest management, as well as a number of other advantages (Mohler & Johnson, 2009).

It has been found that crop rotations that alternate food crops with crops for other uses (e.g., feed, biofuel, or biomaterials) may improve soil quality by, for instance, replenishing nitrogen and reducing soil deterioration. A good case in point is corn in crop rotation with *alfalfa*, a deep-rooted perennial legume. In the United States, this approach has received substantial research; the main findings indicate that this practice leads to an increase of the nitrogen content in the soil, as well as a reduction of nutrient run-off and soil erosion (Jung, 2010).

Another positive example is the so-called Biogas Done Right (BDR) model, developed by Consorzio Italiano Biogas (CIB), and applied by hundreds of farmers in Italy and France (CIB, 2017). This method links anaerobic digestion to sustainable farming to produce biogas, making farms more competitive in the food, feed, and energy markets (C. Rossi, 2016). The crop rotation scheme of the BDR model, based on cover cropping, involves a primary crop for food or feed and a secondary for energy production (Testa et al., 2022). In this way, the increased coverage of the usually bare agricultural land with cover crops also decreases soil erosion (Alberici et al., 2021).

2.1.2 | Crops for phytoremediation

It is well known that food production strongly depends on the quality of soils, being estimated that 95% of our food is directly or indirectly produced on our soils (FAO, 2015). Nutritious and good quality food and animal fodder can only be produced if soils are healthy, as these are able to supply essential, water, oxygen, and root support that food-producing plants need to grow and flourish. However, degraded areas, where soil erosion, contamination, desertification and acidification occur, are constantly expanding and thus remediation is even more essential (Kacprzak et al., 2022). The practice of phytoremediation, which involves removing pollutants (in particular heavy metals) from soils and using green plants, is well known as a promising method for restoring the environment at a reasonable cost and instead of engineering techniques that might be more harmful to the soil. (Gomes, 2012). The utilization of several perennial bioenergy crops for phytoremediation has been the subject of numerous research to avoid or lower soil contamination, which can have a negative influence on nutrition by moving up the food chain (Yan et al., 2020). Bioenergy crops could be grown to remediate contaminated land for later use or as buffer zones to stop pollutants from leaking from contaminated areas.

There are a number of perennial bioenergy crop species that can be used for phytoremediation, for example, *Miscanthus*, *Jatropha curacas*, *Ricinus*, *Populus*, and other plants of the *Salicaceae* family (Pandey et al., 2016; Yan et al., 2020); they can boost soil microbial activity and diversity and raise soil carbon concentration (Emmerling et al., 2017; Pandey et al., 2016). Studies on contaminated brownfield areas in the United Kingdom found that combining mixed poplar and willow trees with *Alnus* species was effective in reducing zinc and cadmium levels (Gomes, 2012; Rowe et al., 2009). In recent years, the ability of willows to absorb heavy metals and organic materials from soil, speed up the conversion of organic materials into nontoxic compounds, control water dynamics, and be used for bioenergy and bioproducts has generated interest as regards their use for phytoremediation in the northeast of the United States (Volk et al., 2006).

Heavy metals from animal effluent can be removed using wetlands species like water hyacinth (*Eichhornia crassipes*), allowing for irrigation of agriculture; the resultant contaminated biomass can be converted to energy by anaerobic digestion or incineration (Hejna et al., 2021).

Other meaningful applicative examples of phytoremediation come from the FORBIO Project (FORBIO Project, 2018) and the De Ceuvel Sustainability Hub (De Ceuvel Sustainability Hub, 2021).

Among its activities, FORBIO (namely "Fostering Sustainable Feedstock Production for Advanced Biofuels on underutilized land in Europe") looked at the application of energy crops for phytoremediation on former sewage irrigation fields on the outskirts of Berlin, classified as contaminated not fit for food production, and on lignite mining reclamation sites in the State of Brandenburg (FAO, 2019), which include raw, barren soils.

De Ceuvel is a sustainable office park built on the site of a former heavily polluted shipyard in Amsterdam North. A careful selection of plants was used to stabilize, break down, and absorb pollutants, while at the same time producing low-impact biomass to be fed, together with other wastes of De Ceuvel, into a digester (Power Plants for

Phytoremediation, 2019); the biogas produced is used to cook in the on-site restaurant (De Ceuvel Sustainability Hub, 2021).

As with many other remediation techniques, phytoremediation calls for caution and safety measures to prevent any unfavorable effects. These include the possibility of biodiversity loss due to increased cultivation of energy crops, nutrient loss in the soil, and high water needs for energy crops (Gomes, 2012; Pandey et al., 2016; Box 1).

2.2 | Linkages between bioenergy by-products and nutrition

This section surveys the available research as concerns the use of secondary outcomes from bioenergy production. More specifically, the application of biochar and digestate to soil for agronomic purposes is here explored, alongside the role of soil quality to produce safe and nutritious food. Indeed, if soil is unable to sustain food production, the addition of fertilizers might be essential. As a matter of facts, chemical fertilizers have been widely utilized to boost agricultural productivity worldwide. In this regard, bioenergy by-products might provide an additional option for soil amendment. Figure 4 provides a brief overview of the main findings of the investigation (Box 2).

2.2.1 | Biochar use

Biochar is the solid carbon-rich product from lignocellulosic biomass pyrolysis (Casini et al., 2021), a thermochemical conversion process largely employed in biofuels production. The physical structure of biochar, as well as its superficial properties, largely depends on factors such as feedstock, reactor type, operating conditions, among others, and the agronomic effects significantly vary on this basis and with different types of soils (Tomczyk et al., 2020). According to studies (Hossain et al., 2020; Murtaza et al., 2021), adding biochar to soil can improve soil health by boosting the concentration of essential plant nutrients including calcium, nitrogen, and phosphorus, fostering soil biological activity, detoxifying pollutants in the soil, and improving soil water-holding capacity.

Kumar et al. investigated the impact of several biochars on sweet pepper (*Capiscum annuum L.*) crop output and disease resistance (A. Kumar et al., 2018). According to the research, adding biochar to the soil had a considerable

BOX 1 Diversification of income through the establishment of bioenergy

Within rural and low-income areas, income diversification is one way that bioenergy might indirectly affect nutrition at the household level. With the help of the appropriate bioenergy policies, farmers might be able to grow energy crops on degraded or marginal land that is unsuitable for food production, or they might be able to rent out a portion of their land to another party for the profitable production of energy crops (Campbell et al., 2008; Faße et al., 2014; Rogers et al., 2016; Sakai et al., 2020; Shortall, 2013). Moreover, farmers may have the possibility to valorize residues or wastes that would otherwise be discarded, resulting in increased overall farm revenues. (Diaz-chavez, 2020). In addition, if the value chain is sustainably built, the growth of the bioenergy sector can promote employment prospects and access to green jobs, particularly in rural regions (Röder et al., 2020; Sakai et al., 2020). The use of bioenergy byproducts in place of chemical fertilizers may increase income, and more effective modern bioenergy cooking methods may result in lower cooking expenses. In fact, this additional revenue may allow households to purchase items they could not afford formerly, providing for greater larger variety (Diaz-chavez, 2020; Kline et al., 2016).

It is essential to note that numerous studies have shown that policies aiming to foster the bioeconomy, whereby bioenergy plays a vital role, are most effective when they place smallholder farmers' support and equity ahead of massive agricultural production (Sakai et al., 2020). Obviously, any modification in crops and agricultural residues designation, as well as land use, for multiple uses might also have unfavorable effects on food security and nutrition. For instance, the reduced use of residues in soil management practices like mulching and biofertilizer may be detrimental to the condition of the soil (Fu et al., 2021; Iqbal et al., 2020). Therefore, interventions should be carefully designed in collaboration with local communities.

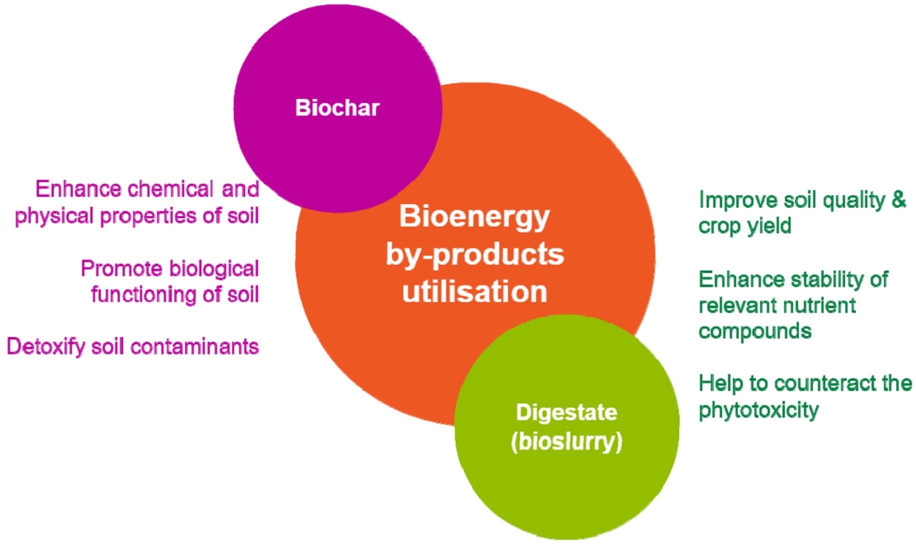

FIGURE 4 Possible uses of bioenergy by-products and potential positive linkages with nutrition.

BOX 2 Healthy soil for proper human nutrition

The negative consequences of soil degradation on the quantity and quality of food production have an impact on human nutrition and health (Lal, 2009). Soil health relates to the ability of soil to carry out ecosystem functions, including biomass production and gross primary output, contaminants biodegrading, climate control, water filtration, storing nutrients and water for plants, and elements recycling (Lal, 2009). Food security and nutrition are directly impacted by soil degradation through reduced yield and lessened nutrient substance of crops, for example, protein content and micronutrients, and also indirectly through decreased input efficiency and the necessity for even more land to balance for the productivity loss (Lal, 2009). In addition, there may be nutrients in the soil that plants cannot reach, which lowers nutrition intake by consumers, a phenomenon known as "hidden hunger" (Pozza & Field, 2020), (White & Brown, 2010). Producing nutritious food will be more difficult without stable soil conditions (Pozza & Field, 2020). Therefore, achieving soil security is vital if better nutrition is desired.

favorable impact on fruit production, fruit quality, and powdery mildew resistance. The analysis revealed that these ameliorations were brought by the effects of biochar on the rhizosphere-pathogen-microbiome plant system, rather than being directly connected to enhanced soil nutrients or adjustments in plant nutritional status. Vijay et al. (2021) undertook a study to investigate the effects of applying biochar on the health of the soil, crop yield, and its potential for carbon sequestration. The research found that adding biochar to degraded tropical soils had a stronger positive impact on agricultural output and soil health. The authors eventually acknowledged that there are fewer biochar field studies compared to the small-scale research projects carried out in labs or greenhouses, indicating that further research in this area is needed. A case study from Ghana (GBEP, 2015) explored possible benefits of using biochar in the scenario where forestry and agricultural waste are turned into pellets that may be used in gasifier cookstoves in place of wood fuel, relieving pressure on forest ecosystems. A case study in Tuscany studied by Chiaramonti and Panoutsou (2019) examines marginal agricultural lands amended by biochar. The research concluded that the use of biochar, which provides long-term benefits to the land by reconstituting the soil matrix, improving porosity, increasing moisture retention, and slowing release of fertilizers can help mitigate these effects and support sustainable agriculture. Moreover, the study determined that the combined use of biochar and compost adds further benefits for the short-term, combining readily available carbon and nutrients with the long-term benefits of biochar. Similar results have been highlighted in the context of the BIO4A Project (EC, 2018), in which both food (i.e., barley) and feedstock for biofuels production (i.e., *Camelina*) were produced on land recovered through the application of biochar which, by bringing organic Carbon back to ground, promoted soil health and fertility.

2.2.2 | Digestate use

Digestate (or bioslurry) is the main co-product from biomass anaerobic digestion, a biochemical process mainly used to convert organic matter into biogas and eventually biomethane. In terms of the biological stability of pertinent nutritional components and phytotoxicity of particular biomass, the use of digestate as a biofertilizer has been proven to have an overall favorable impact when compared to the usage of untreated crops (Paolini et al., 2018). However, according to Möller (2015), direct effects of digestate application on soil fertility are thought to be of low significance in the long run, whilst the largest effect on soil fertility is related to revisions in cropping systems brought on by the installation of an anaerobic digester, such as modified harvesting times, crop residue removal, or crop rotations with new energy crops. A report by FAO in 2013 (de Groot & Bogdanski, 2013) summarized a number of case studies evaluating the effects on crop yield of applying bioslurry in comparison with other fertilizers (organic and/or synthetic) and no use of soil amendments. Based on the type of crop, each study's findings were different. One study (Garg et al., 2005) compared the wheat yield of samples treated with digestate to those not fertilized at all and found that the samples treated with digestate outperformed the samples not fertilized. However, another study (Lošák et al., 2011), that evaluated the yield of Kohlrabi following the application of bioslurry and synthetic fertilizer, found that the yields were comparable. The report (de Groot & Bogdanski, 2013) came to the same conclusion as the previous studies discussed above: although encouraging, the effects of digestate use on soil quality and crop output are mostly equivocal and need further investigation.

The use of digestate as renewable fertilizer is also accounted in the above-mentioned and widely used BDR model. According to the scheme, the wet fraction of digestate is brought back to the cropland using drip-feeding systems (fertigation), which allows all nutrients from biogas crops to be recycled back to agricultural soils (Alberici et al., 2021). Nevertheless, this article (Alberici et al., 2021) does not provide evidence highlighting direct effects on nutrient content of crops.

2.3 | Linkages between bioenergy use and nutrition

This section covers the available literature on the use of modern bioenergy for cooking systems and for chilled food storage, as well as potential effects on nutrition. A quick summary of the main results pertaining this specific step of the bioenergy value chain is shown in Figure 5.

2.3.1 | Modern bioenergy for clean cooking solutions

Where traditional bioenergy use is prevalent, switching from conventional to improved cookstoves (ICS) or other clean cooking solutions, including ethanol or biogas stoves, may have multiple indirect benefits on nutrition by improving health through a reduction of indoor air pollution, as well as dietary diversity.

Improved cookstoves

It was observed that ICS lowers particulate matter concentrations and emissions of carbon monoxide and black carbon, which lowers the incidence of lower respiratory infections and other health problems like headaches and eye irritation (A. Singh et al., 2012). A pilot project in Kenya, aiming to increase the effectiveness of biomass use by promoting the use of gasifier stoves that produce biochar, reported significant reductions in cooking-related indoor smoke as well as efficiency gains (GBEP, 2015). Additionally, users from a case study on ICS in Nepal noticed cleaner kitchens and kitchen utensils after using the ICS solutions (A. Singh et al., 2012).

Suresh et al. carried out a study on the performance of three types of ICS, that is, traditional cookstove, natural-draft ICS and forced-draft ICS (Suresh et al., 2016). When comparing traditional cookstove and natural draft, no substantial difference in indoor concentrations of particulate matter with particles with a diameter of 2.5 micrometers or less ($PM_{2.5}$) and carbon monoxide (CO) was observed; however, the results revealed significantly lower concentrations of

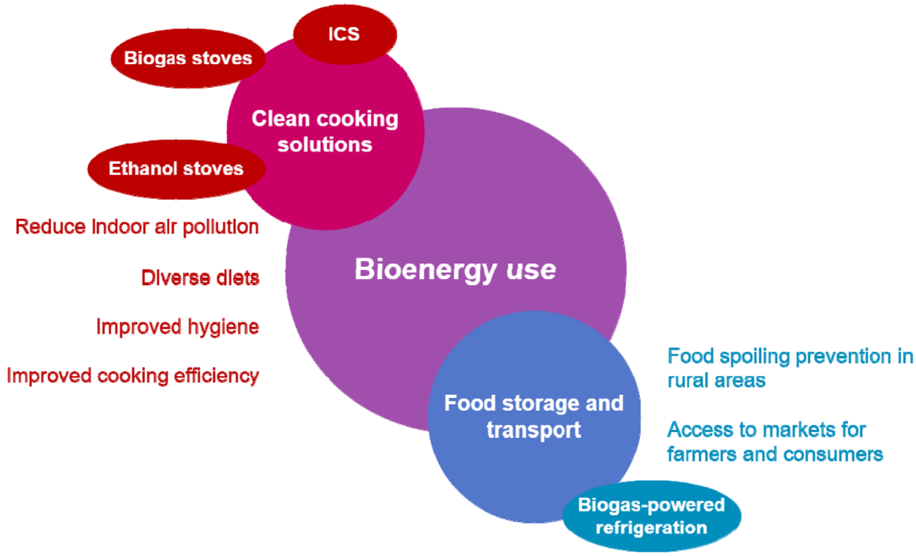

FIGURE 5 Use of modern bioenergy in cooking and food storage.

$PM_{2.5}$ and CO when using forced draft cookstoves. Moreover, all the examined ICS showed shorter cooking times and a lower fuel quantity needed to cook, suggesting that households may be able to have a wider variety of diets, which is in line with Anderman's hypothesis (Anderman et al., 2015).

Biogas cookstoves

During a research project in Southern India (Anderman et al., 2015), biogas cookstoves were found to reduce overall cook times, enhance interior air quality, and enhance cooking efficiency. The study found that, with alternative stoves, users may have even higher control on cooking temperature and time, being thus able to decide to add other items to their diets that would be otherwise too time-consuming or presented a high risk of spoilage due to unmanageable stove temperatures. Thereby, Anderman et al. concluded that cooking efficiency could contribute to greater diet diversity.

Ethanol-based cooking alternatives

In randomized-controlled trials, ethanol cookstoves were found to produce better pregnancy outcomes for users than conventional stoves (Alexander et al., 2018). Furthermore, as demonstrated by trials carried out in Ethiopia (Pennise et al., 2009), ethanol cookstoves may cut average CO emissions by 76% and average $PM_{2.5}$ concentrations by 84% compared to typical biomass cookstoves (Dioha et al., 2012).

Beneficial effects have also been recognized for ethanol-based gel cooking fuel, which is smokeless, odorless, non-poisonous, easy to handle, and can be used in traditional stoves (Biopact, 2006); an applicative example is the *Millennium Gelfuel*, developed and promoted by World Bank in Africa (Utria, 2004).

2.3.2 | Modern bioenergy for food refrigeration

Refrigerating harvested crops and other products is crucial to prevent spoiling, as well as to give farmers access to markets for their agricultural outputs. Nevertheless, the use of traditional cold storage technologies might be limited by the absence of reliable grid electricity in rural areas.

Using biogas, a sustainable energy source, for chilled storage can extend the shelf life of goods (Abrahamse et al., 2019).

The initial capital costs of biogas-powered refrigeration were found to be relatively high in a case study in Kenya involving biogas made from dairy cattle waste (Flammini et al., 2018), but the overall financial and economic returns were good. In addition, the research reported beneficial effects on soil quality, indoor air pollution, fertilizer use and efficiency, food loss, GHG emissions, and access to energy.

3 | DISCUSSION

To our knowledge, this study, which builds upon an initial literature review (GBEP, 2022), was the first to explore and shed light on the possible positive linkages between bioenergy and nutrition, whose nexus is regrettably overlooked.

The analysis showed that, if embedded in integrated and sustainable production systems, bioenergy can offer the potential to support better nutrition through the supply of safe and nutritious food as part of healthy diets but also to minimize health risks associated with traditional bioenergy, and thus contribute to the achievement of both SDG2 and SDG7. This may result in a positive ripple effect on social and economic development, as these two Goals are strongly connected to all the 2030 Agenda Goals.

However, the overall findings of the publications included in this literature review were rather site- and context-specific, making it challenging to draw generalizable outcomes.

The bioenergy and nutrition nexus may open a range of further opportunities for study and debate to better understand the function of bioenergy in nutrition.

3.1 | Feedstock production for bioenergy

The study highlighted that integrated biomass production systems and phytoremediation have a great potential to mitigate land use impacts and increase the ability of the agricultural ecosystem to produce nutritious food, given that healthy soils are the foundation of healthy food (FAO, 2015). Moreover, biomass production for bioenergy additionally provides a good opportunity to diversify income, especially for rural and smallholder farmers, resulting in higher purchase capacity for good quality food. Several agronomic methods coupled with bioenergy were reviewed (e.g., intercropping, crop rotation, BDR), and some applicative examples of positive effects on soil quality and crop yield were found, though limited.

Other studies suggest that phytoremediation utilizing bioenergy crop species might have beneficial effects on nutrition, especially if supported by safeguards to mitigate potential negative outcomes. This approach has the potential to enhance soil quality and eliminate contaminants that could be dangerous to human health in areas where conditions are favorable for phytoremediation and the use of biomass for bioenergy thereafter. The best genotypes for phytoremediation in specific ecosystems are currently being studied, and this is a topic that needs further research.

3.2 | Valorization and use of processed by-products generated along with bioenergy

The evidence reviewed showed that biochar can have multiple positive effects on soil, including: enhanced chemical and physical properties, increased water-holding capacity and plant nutrients, and contaminant detoxification. This, in turn, enhances the potential of the land to produce safe and nutritious food.

On the other hand, the effects of the digestate application as biofertilizer were proven to be generally beneficial over untreated crops, but nonetheless some case studies did not experience relevant improvements in crop yield.

Therefore, we can conclude that the links between the application of these bioenergy by-products as soil amendments and soil health and fertility are related to multiple factors, such as soil type, application regime, climate, and crop.

Even though several positive case studies were found, it is difficult to draw universal conclusions. Moreover, the literature review has shown that further research is still needed to determine whether switching from chemical fertilizers to digestate by-products improves nutrition significantly.

3.3 | Bioenergy use

There are several ways that bioenergy in its diverse forms (e.g., biogas, ethanol, etc.) may be used in relation to nutrition, such as food production, processing, and preservation (e.g., drying and milling).

The available literature demonstrates that transitioning from traditional cooking stoves to ICS or other clean cooking options, such as ethanol and biogas stoves, may have many positive effects, for example, on indoor air pollution and environmental sanitation.

Furthermore, given the higher efficiency of these systems with respect to traditional methods, households might be able to achieve enhanced cooking efficiency, allowing for more foods to be cooked concurrently and effectively, as well as with a greater variety. This last point would be particularly important for some segments of society whose diets are confined to non-nutritious staple foods. However, the high ICS upfront costs and low availability of biofuel might discourage households from making this switch and they might keep relying on traditional cookstoves. To meet the SDG2 targets, healthy diets must be delivered at a lower cost to enable people to access affordable nutrient-rich safe food. Along with indoor air pollution, outdoor air pollution may be another area of research that is worthwhile in the context of the bioenergy and nutrition nexus.

As for food transport and storage, from the evidence analyzed, modern bioenergy to power refrigeration is promising for preventing perishable food spoilage in rural areas with no access to reliable grid electricity. However, the impacts on nutrition appear quite indirect, and the topic is still under-researched. A related topic that could be interesting for investigation might be that of the use of bioenergy for processing and preserving the nutritional quality of non-perishable foods, which also have a paramount role in advancing human nutrition and promoting balanced diets and diversity.

4 | CONCLUSIONS

Understanding the linkages between modern bioenergy and nutrition, alongside the multiple win–win opportunities embedded in sustainable agriculture, is essential to facilitate the achievement of UN SDGs.

Nevertheless, this nexus is regrettably overlooked and the current public perception about their interaction is still chiefly negative. Thereby, the present review was intended to explore and shed light on possible positive linkages between bioenergy and nutrition, identifying examples of good practices applied along the different stages of the bioenergy value chain with potential co-benefits for nutrition.

The analysis revealed that, although multiple studies show that bioenergy has a significant potential to enhance nutrition and attain and promote healthy diets, the existing research in this area is still limited and calls for further investigation.

The strongest links between bioenergy and nutrition emerge when results address common constraints. For example, improved soil health and quality through phytoremediation and integrated biomass production systems can result in enhanced nutrient quality of plant foods. Farmers involved in sustainable biomass production can generate additional income while being able to utilize bioenergy by-products such as biochar and digestate as soil amendments. Clean cooking solutions through biogas stoves, ICS and ethanol stoves can both reduce indoor air pollution caused by traditional stoves as well as contribute to improved environmental sanitation. Finally, in contexts with limited access to reliable electricity grids, biogas can power cold chains, which can help to reduce losses of perishable, nutritious food. Overall, the results of the articles analyzed in this literature review were very site- and context-specific, and conclusions of general validity could not be derived.

Nonetheless, the findings of this investigation may allow researchers to better assess the potential applications of bioenergy to enhance global nutrition and overcome the limits of the food versus fuel paradigm. The bioenergy and nutrition nexus provides great opportunities for future research, to whom the references collected in this review could be used as a base to better define the function of bioenergy in nutrition, highlighting and compiling further examples of good practices within the bioenergy value chain that can help to ensure or safeguard nutrition security.

AUTHOR CONTRIBUTIONS

Lorenzo Testa: Conceptualization (equal); data curation (equal); formal analysis (equal); methodology (equal); visualization (equal); writing – original draft (lead). **Maria Michela Morese:** Conceptualization (equal); supervision (equal); visualization (equal); writing – review and editing (equal). **Constance Miller:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (lead); methodology (equal); visualization (equal); writing – review and editing (equal). **Lorenzo Traverso:** Methodology (equal); visualization (equal); writing – review and editing (equal). **Tiziana Pirelli:** Methodology (equal); visualization (equal); writing – review and editing (equal). **Patrizia Fracassi:** Conceptualization (equal); formal analysis (equal); methodology (equal); supervision (equal); visualization (equal); writing – review and editing (equal). **Tomoko Kato:** Conceptualization (equal); formal analysis (equal); visualization (equal); writing – review and editing (equal). **Caitlin McGinnis:** Data curation (supporting); investigation (equal).

Marco Colangeli: Visualization (supporting); writing – review and editing (supporting). **David Chiaramonti:** Supervision (equal); visualization (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data available on globalbioenergy.org.

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