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Sustainable Alternatives for Energy Generation and Food Production in Brazil

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Abstract

Urbanization driven by industrialization and population growth amplifies food consumption and reinforces the need for more fuels and energy. However, the expansion of biofuels can impose risks on long-term food security. This paper examines potential alternative crops for energy generation and food production, including those used by family farmers and their associations, to decentralize energy production and utilization as a crucial pillar of the global energy transition. Cassava, corn, and sugar beet are the chosen crops, and their performance is compared with that of sugarcane as a reference to consolidated agriculture crops. Four scenarios are proposed and calculated, considering 10, 20, 30, and 40 million hectares of agricultural land to be transferred to family farmers for cultivation of the proposed crops. The crop production, ethanol production, and the resulting emissions are assessed and compared. The results show that the three investigated crop options are viable and interesting for balancing fuel and food production. The results show that for the case of 40 Mha, the crop production of sugar beet is 1600 × 10^6 ton and ethanol production of 400 × 10^6 m^3, while the cassava produces 1400 × 10^6 ton of crop with ethanol production of 280 ×

10^6 m^3. Compared to sugarcane whose ethanol energy content is 10,108.8 × 10^6 GJ, the sugar beet ethanol energy content is 9,560.0 × 10^6 GJ while cassava ethanol energy content is 6,552.0 × 10^6 GJ. The CO_2eq emissions due to ethanol production, sugar beet produces 162.8 × 10^6 tCO_2eq while cassava produces 288.68 × 10^6 tCO_2eq and sugarcane produces 107.15 × 10^6 tCO_2eq. The findings show that sugar beet and cassava are adequate candidates to attenuate the demands for more food and diversify resources for ethanol production. The novelty of the present work is the inclusion of family farmers in the command of cultivation of the new crops and management of the production of biofuels and creating strategic food reserves to control food price of the internal market and avoid the impacts of the external food markets on the internal market. The diversification of biofuel sources is welcome to reduce pressure on land for food production, reduce fluctuations of offer and demand of biofuels besides maintain sufficient food offers at affordable price, conditions which are recommended by the United Nations Organization (SDG 2 and SDG 7) and necessary for sustainable energy transition.

Keywords
Food security; energy security; family farming; energy transition; cassava; corn; sugar beet; sugarcane; ethanol; biofuels

1. Introduction

One of the consequences of industrialization is the demographic expansion with a big concentration in the urban areas, which led to a substantial increase in food consumption, electricity, petroleum products, and emissions. The world's population grows by an average of 1.13% per year, and it is estimated that in 2050 there will be 9.6 billion inhabitants on Earth [1]. Developing countries are expected to experience higher population growth, with approximately 70% of the world's population projected to be urban [2]. With this scenario, there will be a greater increase in food and energy consumption, and the current sources will not sustain the future populations and their demands for food and energy, and consequently, food and energy security will be at risk [1-3].

The use of fuels with less environmental impact, associated with the concept of energy efficiency, is one of the sustainability pillars, allowing for the better use of natural resources. The energy efficiency indicators and reduction in environmental effects across various economic segments are global issues, particularly in the context of the global energy transition [4-6].

One major consequence of the demographic expansion is the abundance of family farming and small agriculture activities in rural areas, which limit food production capacity and can threaten food security affecting principally poor nations with poor agricultural lands. This possible situation always urged the UN to emit alert reports to encourage nations to adopt adequate policies for food security. There is a need for a global effort and investments in these regions to create adequate infrastructure, train the populations, implement community projects and initiatives for solidarity projects to create jobs and income and ensure access to food and health.

Another consequence of the demographic expansion is the need to increase biofuel production.

This can seriously affect food production and food security in the long term since both depend on land and water for possible expansion. Large biofuel producers usually target land for biofuel production (ethanol) due to market value, rather than food production [1]. However, if there is an incentive for small producers and family farmers to plant and diversify the raw material of biofuel production, there can be a balance between planting for food production and energy production [3].

World economic development is based heavily on fossil fuels. The production of these fuels will not be sufficient to meet world demands [7]. According to the report of the IPCC, Intergovernmental Panel on Climate Change, the temperature of the planet has already increased by about 0.8°C, in order not to reach 2°C, a reduction of CO_2 emissions of around 50% to 80%, will be necessary [8, 9]. Many investigations and developments are currently devoted to assess the viability of producing fuels (ethanol, biodiesel and biohidrogen) from agriculture and food wastes as second generation biofuels with less impact on food destined land and at the same time reduce the impacts of these organic wastes on emissions, urban waste management, besides enhancing circular economy. Biofuels can be classified into first, second, third and fourth generations where each has distinct properties depending on the raw material and production technology. First generation biofuels are obtained from food sources such as sugarcane, soy and wheat to produce ethanol and biodiesel and hence their production competes with food resources. Second generation biofuels are produced from raw materials such as wood, grasses and agriculture and food wastes and do not compete with food resources. The third generation is produced from algae and other microorganisms. The fourth generation utilizes genetically modified organisms such as algae as raw material but still under tests laboratorial. The second generation bio-fuels are therefore, bio-renewable fuel sound ecologically, viable economically, does not threaten food security and can improve waste management [10-12].

Among the solutions proposed at the moment and in the near term is the increase of the share of biofuels in the global energy matrix, which means the increase of the land destined to produce energy products and this will naturally affect the global food security. Figure 1 shows the world ethanol production and consumption from 2012-2020 showing a slight decrease in 2020 due small production and consumption during the Covid-19.

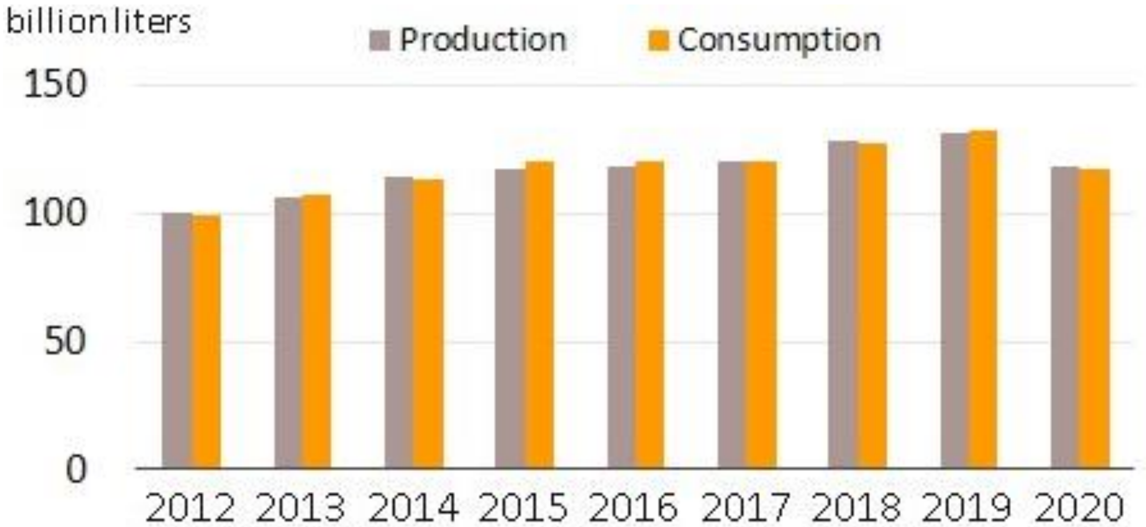

Figure 1 Evolution of world ethanol production and consumption from 2012-2020 [13].

Figure 2 shows the contribution of some countries to the global production and consumption of ethanol in 2020. As can be seen Brazil occupied the second position behind USA while China occupied the third position.

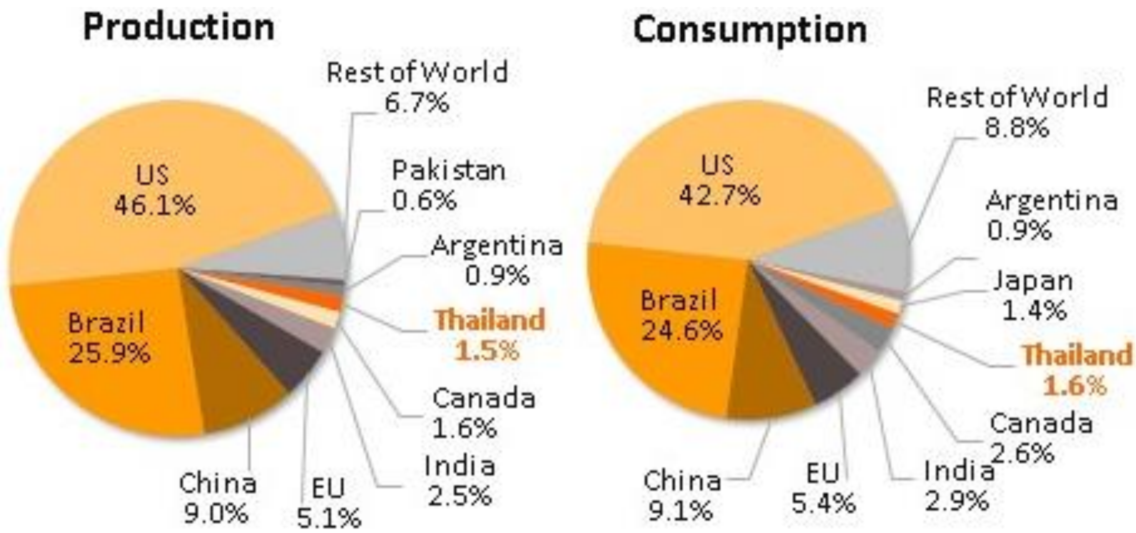

Figure 2 Global ethanol production and consumption in 2020 [13].

As shown, energy and food needs are continuously increasing with the global population growth, the expansion of industrial activities in developing countries, and improvements in lifestyle and consumption patterns. This suggests that current resources for food and energy may be insufficient for future generations, and some actions need to be taken to prevent disastrous consequences. This possible scenario prompted the authors to propose investigating alternative agricultural approaches to address increasing food and energy demands, as well as the introduction of family farming and associations in the production, generation, and decentralization of energy and food products.

The continuous increase of the world population, global migration of farmers to industrialized regions for better income besides the global tendencies to link food prices to global speculative investments and regional conflicts threatens the global food security. The recent years showed how these global issues drastically affected food prices worldwide with strong impacts on poor populations and poor countries. Global food security needs global collaboration of all nations to reduce crop losses, reduce food losses, create reserves for food, and collaborate in global manner to supply food and basic elements for poor nations. These efforts can include offering technological and financial help to improve the local production conditions in poor countries beside engaging these nations in global industrial and agriculture activities and efforts. These actions along with others may help to reduce global poverty and improve local living conditions of these populations.

Hence, the main objective of the study is to investigate corn, root beetroot, and cassava as possible alternative agriculture crops for bio-fuel and food production and, introduce family farming and their cooperatives in these processes, and create basic food reserves as barriers against international food price oscillations. This can help facing ever increasing energy and food needs, besides attending the UN developments goals SDG 2 (Zero hunger and sustainable agriculture) and SDG 7 (Clean and accessible energy) [2].

The idea of proposing sustainable alternative crops for the production of biofuels and allocation of additional agricultural land to family farming is in line with the current Brazilian public policies (*Pronaf- Programa Nacional de Agricultura Familiar e PNPIAF- Programa Nacional de Pesquisa e Inovação para a Agricultura Familiar e Agroecologia*). This strengthens family farming, produces more food to attend the poor population, creates strategic and emergency basic food reserves for internal price control and protection against international prices oscillations. This also promotes social inclusion, promotion of energy transition policies and decentralization of food and energy productions. The diversification of bio-fuel sources is welcome to reduce pressure on expanding areas specifically for energy production, reduce fluctuations of offer and demand of bio-fuel and hence keep stable price for bio-fuel besides sufficient and alternative food offers.

The contribution of this paper is the inclusion of family farming in the plantation of additional food crops, create emergency food reserves to maintain stable internal prices and create barriers against external price oscillation of both energy and food, besides creating jobs and income, and contributing to the social inclusion of poor families.

2. Food Security, Energy Security, and Family Farming

2.1 Food Security

Food security ensures availability at all times of adequate world food supplies of basic food elements to sustain a steady expansion of food consumption and to offset fluctuations in production and prices.

Eradicating hunger and malnutrition is one of the significant challenges since lack of enough food impacts health as well as progress in strategic areas like education and employment. In 2015 the global community adopted the 17 Global Goals for Sustainable Development to improve people's lives by 2030. Goal 2 – Zero Hunger – end of hunger, achieves food security, improves nutrition and promotes sustainable agriculture. About 29.6% of the global population – 2.4 billion people – were moderately or severely food insecure in 2022, of which about 900 million (11.3% of people in the world) were severely food insecure [2, 3, 14]. Domestic food price inflation remains high around the world [15]. Some important actions are necessary to help eliminate hunger, including investing in family farming, reducing food waste, providing affordable, nutritious diets, and ensuring universal school meals.

Aborisade and Bach [16] conducted a study to examine the role of four independent variables in respect to sustaining Global Food Security: food availability, access to food, nutrient utilization, and food stability, which are usually referred to as the Pillars of Food Security. The authors presented a model to illustrate the relationship between food security and its sustainability. The model shows that besides availability, access, utilization, and stability other sub-factors must be considered in developing a sustainability strategy. Abdulkadyrova et al. [17] conducted a study on global food security problems in the modern world economy. The food problem is mainly due to overly intensive use of natural resources, increasing per capita food consumption and other factors leading to a steady rise in food prices and an eminent threat to food security for relatively poor countries and populations. The control of increase in prices for food is a decision for both developed and developing countries. Baer-Nawrocka and Sadowski [18] conducted a study to identify the current status of food security in different countries considering physical and economic availability combined together. The study revealed the extent to which food security is ensured through domestic supply, which varies globally. Domestic production provides a foundation for food security in wealthy countries, usually located in areas with favorable conditions for agriculture.

2.2 Energy Security

Energy is one of the essential pillars for the maintenance, continuous growth and development of any country. For a long time, the provision of this energy for operating industrial and transport sectors, among others, was mainly through petroleum, which led to the deterioration of the ecosystem, serious global heating, and its disastrous consequences, alerting for uncontrollable consequences for life on earth. This triggered enormous actions and efforts worldwide to reduce these effects and invert the situation if possible. Intense global investments, big projects and continuous developments are needed to replace fossil-based fuels and products by other renewable energy sources, use of biomass to generate energy especially fuels (ethanol, methanol, biodiesel and bio-hydrogen), use of the bio-refinery concept to produce chemical products and fuels from agriculture and food wastes, use of urban solid wastes and sewage to generate biogas and promote circular economy.

2.2.1 Bio-Fuels (Ethanol)

Biomass is used to produce biofuels of high potential to substitute fossil fuels and reduce greenhouse gas emissions. These biofuels can be classified into four generations, and each has distinct properties depending on the raw material and production technology. First-generation biofuels are obtained from food sources such as sugarcane, soy, and wheat to produce ethanol and biodiesel, and hence their production competes with food resources. Second generation bio-fuels are produced from raw materials such as wood, grasses and agriculture wastes and do not compete with food resources. The third generation is produced from algae and other microorganisms. The fourth generation utilizes genetically modified organisms such as algae as raw material. Both the third and fourth generations are still in laboratorial stage. The second generation bio-fuels is a bio-renewable fuel that sound ecologically and economically viable and do not threaten food security, and can improve waste management [10, 19-21].

2.2.2 Biodiesel

Vegetable oils are often used for the conversion of methyl or ethyl fatty acid esters. Table 1 presents the processing methods of first-generation biodiesel. Reduction of carbon monoxide, particulate matter and exhaust soot emissions have been observed for all biodiesel mixtures [11].

Table 1 First generation biodiesel adapted from [11].

Biomass	Processing method
Waste cooking oil	Esterification - Transesterification
Food crops	Extraction - Transesterification
Organic oils	Hydrolysis - Distillation
Animal fat	Hydrolysis - Fermentation

Again, the production of first-generation biodiesel competes with food needs and can represent a future threat for food security. Extensive efforts are directed to the second-generation biodiesel, where agriculture and food wastes can be used, Table 2. Intensive research work is dedicated to the third and fourth generations where there are no conflicts between bio-fuels and food needs, Table 3 [11].

Table 2 Biofuel generations with processing technology, adapted from [11].

Generation	Biomass used	Processing method	Generated fuel
1st	Food crops, edible oil, animal fats	Transesterification - Thermochemical processing	Bioethanol, biodiesel
2nd	Waste cooking oil, rice and wheat straw, non-edible oils	Pre-treatment - Chemical, biologiical, physical, fermentation and Thermochemical processing	Syngas, biobutanol, biodiesel
3rd	Algae and microorganisms	Cultivation - Extraction - Fermentation - Thermochemical processing	Methane, bioethanol, biobutanol, syngas, biodiesel
4th	Algae and microorganisms		Biodiesel, methane, biobutanol, bioethanol

Table 3 Advantages and disadvantages of biodiesel generations, adapted from [11].

Biodiesel generation	**Advantages**	**Disadvantages**
1st generation biodiesel	1. Low emission of greenhouse gas. 2. Easy and low-cost technology for conversion.	1. Yield is inadequate to meet the demand. 2. Causes food shortage. 3. Highland footprint.
2nd generation biodiesel	1. Using food waste as a feedstock. 2. Use of non-agricultural land to grow a limited amount of crops.	1. Costly pre-treatment. 2. Sophisticated technology is used to transform biomass into fuel.
3rd generation biodiesel	1. Simple to grow algae. 2. No competition for the use of food crops: wastewater, seawater can be used.	1. More resources usage for algae cultivation. 2. Low lipid level or biomass accumulation in algae.
4th generation biodiesel	1. High biomass and production yield. 2. More capability to eliminate CO_2.	1. The cost of the bio-reactor is higher. 2. At the early stage of research, the high investment needed.

Awogbemi et al. [22] presented a review on the development and utilization of agricultural wastes in the production of biodiesel. The authors reviewed recent trends in converting and utilizing agricultural wastes as heterogeneous catalysts for biodiesel production and concluded that catalysts derived from agricultural wastes offer a cheap, readily available and easy to produce.

However, the production of biofuel crops, especially crops for the production of first generation bio-ethanol and biodiesel, can also have negative impacts on the environment, particularly through land use change and deforestation. Moreover, biofuels require water and land resources that may otherwise be used for food production. Therefore, the competing needs for land and water resources by food and biofuel sectors are currently in debate including the effects on food security, environment, and the displacement of land use [11, 23].

Glycerol is sub-product from the production process of biodiesel, abundant and inexpensive, and available research results show that it can produce fuels and chemical products at yields higher than those obtained using common sugars. Production of ethanol from glycerol provides a unique opportunity for the biodiesel industry to generate another biofuel from biodiesel wastes. Chilakamarry et al. [24] investigated the conversion of glycerol waste to bio-ethanol. The waste glycerol is used as a good and cheap carbon source as a substrate to synthesize ethanol. However, the glycerol main limitations in fermentation processes are related to the presence of impurities and the lack of nitrogen sources, both acting on microbial activity. The fermentation process with glycerol was improved using a highly specific microbial consortium. The process was developed in fed-batch fermentation mode [19].

Ong et al. [12] presented a review of recent advances in biodiesel production from agricultural products and microalgae using ionic liquids (IL). The role of IL catalyst in intensified biodiesel production methods such as microwave and ultrasound technologies was also discussed, besides the prospects and challenges of IL catalyzed biodiesel production.

Biofuels are considered the natural substitute for fossil fuels, especially in transport systems, including road, air, and marine transport. The transport system is a big consumer of energy and a substantial contributor to greenhouse emissions. Biofuels are eco-friendly and can be produced from agriculture crops and agriculture and food wastes. Hence can help in the management of urban and rural wastes, besides generating biofuels such as ethanol, methanol, biodiesel and bio-hydrogen, and other chemical products and elements for industrial use.

To achieve the objectives of strengthening the role of biofuels in energy transition some issues has to be considered:

1. More research and developments on the use of agriculture and food wastes for the second generation of biofuels (ethanol and diesel).
2. Research and more development to use Glycerol, a sub-product from the biodiesel production process to produce ethanol and chemical products.
3. Create financial incentives for investigating new resources for biofuels in third and fourth generations to eliminate resource conflicts between food and energy.
4. Public policies and financial and tax incentives for initiating industries in the energy sector.

2.3 Family Farming

Family Farming is a means of organizing agricultural, forestry, pastoral and aquaculture production, which is managed and operated by a family and predominantly reliant on family labor [25]. Family farmers carry out a highly important socioeconomic, environmental and cultural function. Family farming involves almost 1.5 billion people worldwide and produces more than 80% of the food in the world and manages around 70-80% of farmland worldwide.

Family farming helps to generate jobs and income in rural areas and improves the sustainability of the activities of the agriculture sector. In this way, Family farming helps the growth of the

Brazilian economy and the welfare of the population and helps maintain them in the rural areas.

In Brazil, family farming occupies an area of about 80.9 million hectares, which represents 23% of the total Brazilian agriculture area. According to the Brazilian Agriculture Census of 2017, [26, 27] about 77% of the agriculture establishments in the country are classified as family farming, employing more than 10 million in September 2017 which corresponds to 67% of the total occupied manpower in family farming. These small farmers are responsible for producing a variety of agriculture and animal products. Hence, family farming is an effective means of contributing to the economic growth of small urban centers, the generation of jobs and income, directly reducing migration to urban areas, and contributing to a better distribution of income in the country. According to the census, family farming forms the economy base of about 90% of the Brazilian municipalities of population of 20 thousand habitants.

Brazil has its economy heavily based on agribusiness, which represents about 25% of the national GDP in the last three years, with the agricultural sector, excluding livestock, accounting for about 18.5% [28]. A large part of this contribution to the economy comes from commodities such as soybeans and corn produced by the large agribusiness sector. However, small agricultural areas account for about 75% of the number of rural establishments, employ 70% of the workforce in the field, have a more varied production, and contribute about 23% of the country's agribusiness [29].

In recent years, the world suffered from high food prices due to local wars and other geopolitical issues affecting the world population and mainly poor nations. Although Brazil is a big exporter of food and meat, the population suffered from the oscillation of food prices and less availability of the products induced by external political, production, and local issues. This led to very high food prices affecting the population and mainly the poor population. This alerted the authorities to expand and intensify family farming as a tool to provide food at stable prices accessible to the population, and create strategic food reserves as barriers against international food price oscillations. This is in line with the basic ideas behind this paper.

To strengthen family farming and make it an active tool to reduce food price oscillations, create reserves for essential basic food elements, and protect the internal market from international variations of prices of food elements and energy, it is essential to develop public policies and induce actions towards these objectives. Actions can include:

1. Distribute the additional area of 40 Mha all over the different regions of the country to avoid centralization and help improve the different regions of the country.
2. Provide financial funds at low interest for the plantation.
3. Provide means for acquiring modern the plantation and collecting equipment.
4. Provide technical information for family farming on agriculture techniques, finance, and administration of their projects.
5. Help create the necessary infrastructure for transport of products and storage of crops.
6. Facilitate the creation of associations and organized movements to facilitate commercial and financial transactions with family farming associations.
7. Facilitated access as official funds, subsidies for implementation and plantation.

3. Materials and Methods

3.1 Sugarcane

In this study, sugarcane is used as a reference crop to serve for comparison with beetroot, corn and cassava. Considering its components including sucrose, fibers, water, and others, sugarcane's energy content is approximately 1060 kcal/kg. By removing from this amount, the energy contained in the fibers (bagasse), the calorific value for sugarcane reaches about 620 kcal/kg. Molasses with about 55% reduction of sugars by weight is capable of producing around 350 liters of alcohol/t [30, 31].

In Brazil, 2023/2024 sugarcane crop is forecast to reach 661.4 million metric tons, which is 6.5 percent more than 2022/23, because of favorable weather conditions and high sugar prices. Figure 3 shows the evolution of the Brazilian sugarcane production, while Figure 4 shows the evolution of the sugar-ethanol production mix in Brazil.

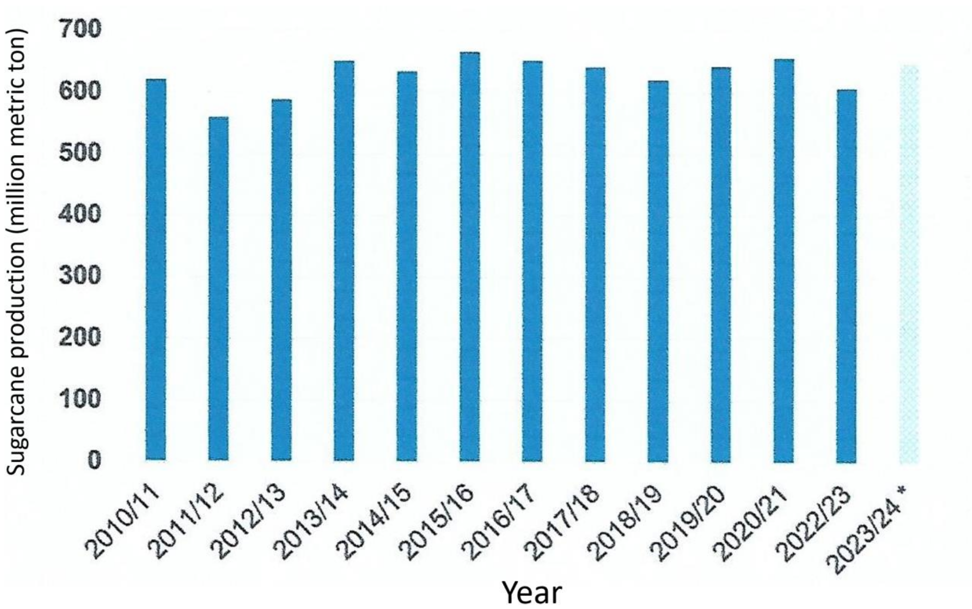

Figure 3 Brazilian sugarcane production (million metric tons) [31].

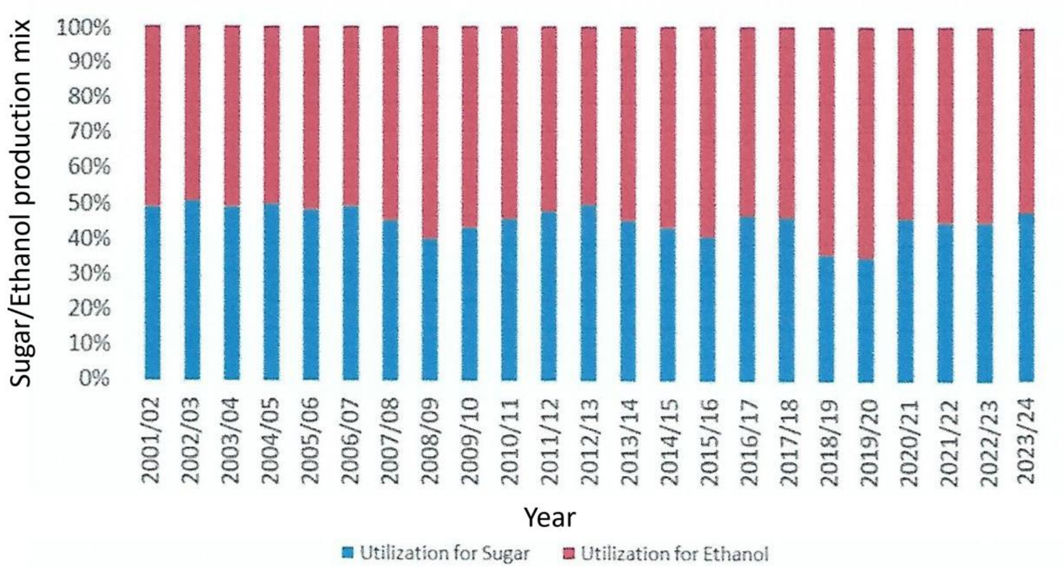

Figure 4 Sugarcane breakdown: sugar/Ethanol production mix [31].

Sugarcane is one of the most important crops of the Brazilian agribusiness. The national average yield is close to 79.5 tons/ha; meanwhile, in traditional regions of sugarcane production, the sugarcane yield can reach more than 89 tons/ha [32]. Sugar content greatly varies due to weather conditions with an average variation of 12 to 13% [33].

3.2 Beetroot

Beetroot, a vegetable, is native to Europe, North Africa, and West Asia. Beet culture is more adapted to the mild climate with an average temperature between 15°C and 18°C, tolerating variations from 4°C to 24°C [31]. Sugar beet juice contains high levels of sucrose and is second only to sugarcane as the major source of the world's sugar. Beet sugar now accounts for almost all sugar production in the European Union and for about one-fifth of total world production.

Sugar beet has high sucrose content in the range of 16 to 21% and represents a possible alternative for the production of ethanol in Brazil with a production rate of about 80 to 95 liters per ton of sugar beet. Sugar beet besides being used for producing sugar, the side products can be used for producing ethanol, biogas, and animal food [20].

In the extraction of sugar from beets, residual products are generated, which are rich in minerals and have easy digestibility, making them suitable for use in animal food supplementation. The beet pulp has great nutritional value for the production of meat and milk, thus being destined for the animal feed industries. One disadvantage of beetroot is energy consumption during processing [34, 35].

The literature reveals that there are many uses for secondary products obtained during the processing beetroot, including beet pulp which can be pressed into plates and enriched with molasses used as fodder for cattle, and pigs. Molasses can also be sold and used as a basis for the manufacture of alcoholic beverages or as a substrate for the production of bread yeast.

Sugar beet needs to be replanted every year with seeds, and sugarcane plantations only need to be renewed every six years, which counts as an advantage. The fact that they are planted with seeds cannot be considered as a negative point, since this can be overcome by planting in a laboratory, and when the time for replanting, the laboratory plants are used in the open camps [36].

Bagasse is a by-product of sugarcane, usually used in the fuel industry to generate electricity. Beet mills, on the other hand, typically generate electricity by burning coal, gas, or diesel oil, non-renewable sources, which increase the cost of sugar or ethanol and also increase the associated emissions. Through incentive programs and adequate public policies, it is possible to use beet scum also for biogas generation during production as an energy source.

The consumption of energy, water, and waste production during the production and planting processes of sugarcane and beets are parameters that should be analyzed, including the use of fossil fuels, wasteful water use, soil degradation, and other factors. Sugarcane contributes 241 kg CO_2/ton, while beetroot 900 kg CO_2/ton, the difference is mainly due to the use of sugarcane bagasse for power generation in the processing plants. Despite the above data on the use of fossil sources, which can be changed, sugar beet is of particular interest as an alternative, because it uses 50% less water than sugarcane from sowing to harvest to produce the same volume of sugar. This factor is of great value for a strategy of diversification of production in Brazil. In addition, the land use requirement is lower with beetroot using 50% of the arable land needed to produce the equivalent volume of sugar with the same area of sugarcane [21, 30, 37].

The Brazilian potential for the production of beetroot is in farms belonging to family farming, which today represent 80% of the country's agricultural establishments. In an area extension, family farming occupies an average of 80.9 million hectares, which represents 23% of the total area of Brazilian agricultural establishments. Some data show that 70% of the food consumed in Brazil comes from these small producers. The inclusion of beets in family production can contribute to the dissemination of this nutrient-rich and diversified food in terms of its use, contributing to the income of these families, creating more jobs, and help eradicate poverty, besides contributing to the expansion of the Brazilian renewable energy matrix [14, 32, 38].

In Brazil, beetroot yield is estimated in the range of 11 to 39 ton/ha wet basis (wb), only the roots [36]. Some experiments in different regions in Brazil reached higher yields between 50 and 80 tons/ha [39, 40], demonstrating the potential for Brazil to reach the worldwide yield of 50 tons/ha wb and may be close to the yield of the ten biggest producers of about 80 ton/ha [31]. Sugar content of beet usually varies between 12 to 18% wb [34, 35], meanwhile, in Brazil, the beet varieties have lower sugar content in the range from 8 to 9% wb [36, 41].

3.3 Corn

In the period of 1991-2021, the expansion of corn agriculture increased significantly. In 1991 the production was 24.1 million tons, while in 2021; the production was 87.1 million tons, or an increase of 261%. The productivity in 1991 was 1.79 ton/hectare, while in 2021 was 4.36 ton/hectare or an increase of 143%. This substantial increase is due to using machinery for all steps of implantation besides the new markets for internal use and exportation. The production of ethanol from corn achieved 5.86 million meters in 2023, or about 15.8% of the total production in Brazil [26-28, 32, 38].

Corn has a strong contribution to Brazilian agribusiness with 13% of the total [28, 29]. The increase in productivity has been highlighted over the years and projections for the next harvests indicate a 32% increase in the domestic market. This high production is linked to growth in animal production divided into cattle, pigs, and poultry.

The corn plant can be used in its entirety. Straw and cob are by-products with high calorific value and high cellulose content essential for second-generation ethanol. The dry raw material has up to 75% starch which is the essential raw material for the basis of the composition of various types of industrial products, including glucose used in the pharmaceutical industry. Ethanol from corn has an average yield of more than 400% of the yield of sugarcane ethanol per liter per ton. These parameters of production, energy generation, food supplementation, and the possibilities of implantation within the family farming program make corn a potential alternative candidate for energy and food together with sugarcane [29, 33].

Corn is one of the most important crops of the Brazilian agribusiness. Thus, one can infer from IBGE [33] that the national average productivity is approximately 6.1 t/ha wb, and studies indicate that it is possible to achieve productivity between 11 and 18 t/ha wb depending on the management strategies used [42, 43]. Corn has, in average, a starch content of around 65% wb [44].

3.4 Cassava

Brazil is considered one of the big producers of cassava, occupying the third top position after Nigeria (43,410,000 t) and Thailand (26,915,541 t). Brazil, in 2023, had little more than one million planted hectares, produced 18,514,317 t with a productivity of 15.41 t/ha. Figure 5 shows the evolution of the production of cassava root in Brazil [38]. The production of cassava was stimulated by the diversified application of the amide in fermented and modified forms or in natural. Cassava flour, which is a food widely consumed in Brazil, always makes the internal market a factor to reduce investment risks.

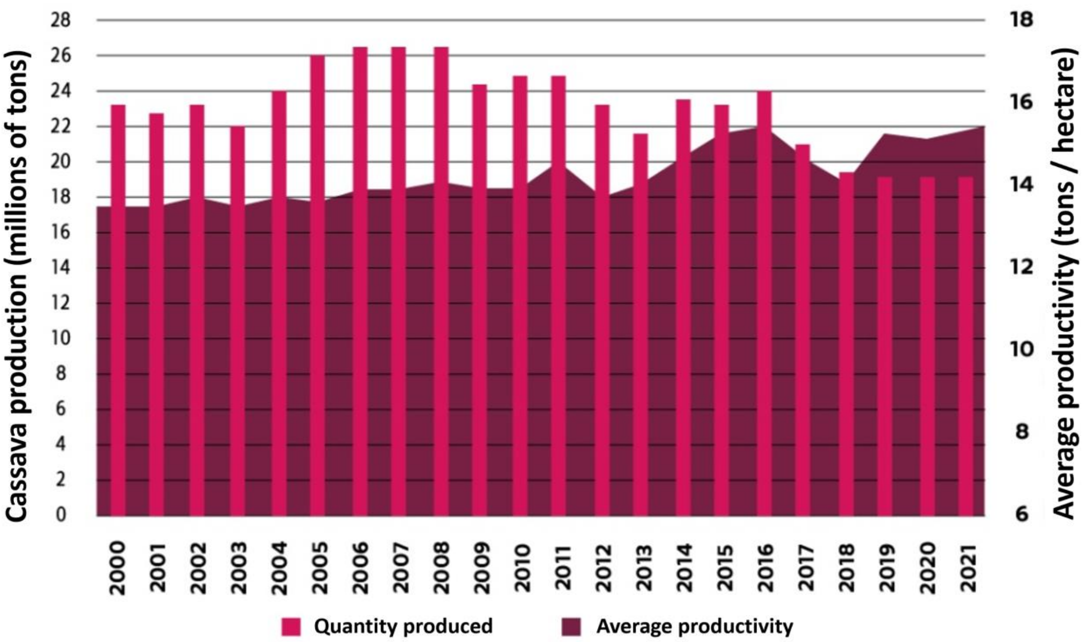

Figure 5 Evolution of the production of Cassava root in Brazil [39].

The Brazilian government incentives to grow cassava for ethanol production began in 1975, since the beginning of the implementation of the “Pro-alcohol” program.

The ethanol generated from the conversion of lingo cellulosic biomass into fermentable sugars demonstrates the potential for substitution of petroleum-derived fuels since lingo cellulosic biomass is a renewable and abundant material, composed mainly of cellulose, hemicellulose, and lignin. Cassava is cellulosic biomass characterized by containing high carbohydrate content that can be converted into fermentable sugars for ethanol production. This makes the use of cassava residues for ethanol production interesting and relevant [45].

Cassava cultivation favors small local producers, which consequently generates important regional socioeconomic benefits. The plant's resistance to factors such as soil quality or lack of rainfall reduces the risks for the small producer. Specific characteristics also favor the small producer, such as the existence of a variant with more sugars, either for commercialization or even for participation in ethanol production processes.

Available results show that it is possible to produce 274.3 liters of ethanol per ton of cassava bark, characterizing cassava husks as efficient biomass for ethanol production, besides being a sustainable and promising alternative for energy generation and valorization of agro-industrial waste [45].

Cassava has a regular world yield close to 15.5 t/ha wb [32], meanwhile, Brazil has an average close to the world average, but some regions have higher yields reaching from 30 to 40 t/ha [20, 45, 46]. The current average of modern cassava genotypes is higher than traditional varieties and varies from 30 to 37 t/ha wb [47].

3.5 Production, Yield and Ethanol Conversion Efficiency

The comparison of the productivity of the investigated agriculture crops in tons per hectare, Figure 6, shows the high productivity of beetroot in comparison with the other crops. This can be explained by the fact that beetroot is a small plant and, therefore, does not need a big distance between the plants to receive the incident solar radiation, and consequently, the density of plants per unit area is higher than the others.

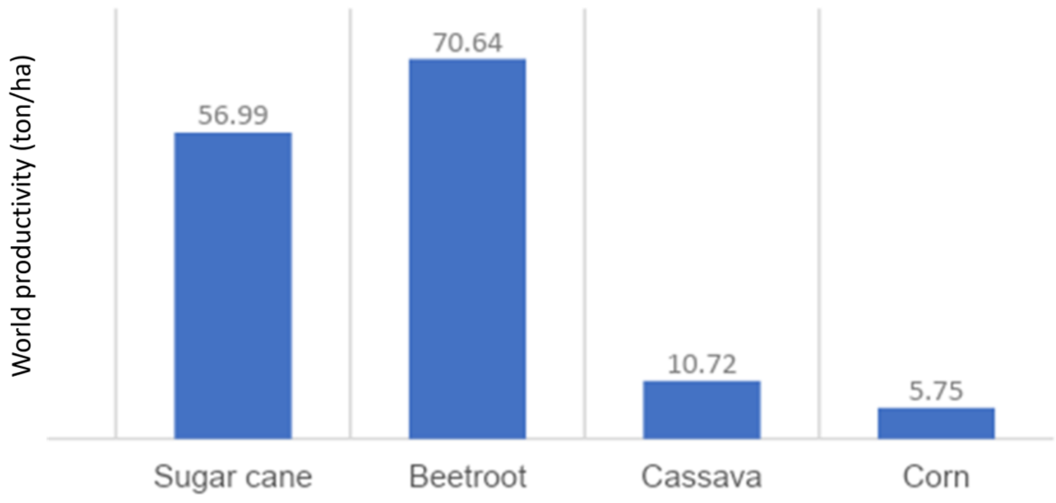

Figure 6 World productivity (t/ha) of sugarcane, cassava, corn and beet root [48].

Although sugar beet is of high productivity, it is important to mention that it is not widely planted in Brazil in comparison with sugarcane, which assumes a dominant position in national agriculture. According to FAO [14, 48, 49], sugarcane is responsible for about 85% of the total sugar production in the country. This significant difference in comparison with the other three investigated crops can be attributed to biofuel policies.

Agriculture crops containing considerable amounts of carbohydrates (sugars) are potential candidates as raw materials for obtaining ethanol besides providing food for the population. The increase in the variety of raw materials for the production of green energy and food contributes to the main targets of sustainability, the diversification of the energy matrix, increase and diversification of the food supply to sustain stable internal food prices, create food reserves and barriers against external market price oscillations, creation of jobs and income and helping to eradicate poverty.

The production and crop yield data vary in function of land fertility, ambient temperature, solar radiation and humidity, irrigation or no irrigation, used fertilizers, quality of sements and agriculture care among other factors. Hence, to choose yield data, we had to consult many references, both national and international. We used the international data as a guide but concentrated our efforts on national data since the work is done in Brazil.

Table 4 summarizes the current scenario of production and yield worldwide and in Brazil, while Table 5 shows the ethanol yield (m^3/ha) of the investigated crops.

Table 4 Crops production, area, and yield of the considered crops [26, 27, 31, 39, 42].

	World			**Brazil**		
Crop feedstock	Area (10^6 ha)	Production (10^6 t)	Yield (t/ha)	Area (10^6 ha)	Production (10^6 t)	Yield (t/ha)
Sugar beet	4.39	270.16	61.41	-----	0.13	11.00-40.00
Cassava	29.65	314.81	12.4	1.18	17.65	14.94-35.00
Corn	205.87	1,210.24	5.88	21.04	109.42	5.20-14.50
Sugarcane	26.35	1,859.39	9.87	9.87	724.43	73.39-89.10

Table 5 Ethanol production and yield of the considered crops [38, 50].

Crop feedstock	**Ethanol yield (m^3/ha)**
Sugar beet	10.0
Cassava	7.0
Corn	4.6
Sugarcane	10.8

3.6 Methodology

For this investigation, the agriculture crops: beetroot, cassava, and corn and sugarcane were used each at the time in four scenarios of 10, 20, 30, and 40 million hectares of additional agricultural land. This land is to be transferred to family farmers according to public policies destined for social inclusion and energy transition. It is considered that the resulting agricultural crop is used entirely for biofuels and food, including wastes and remains.

The following sources of information were used:

- IBGE [26, 27, 33, 39] and FAO [48] were used to obtain the production data for the Brazilian regions related to sugarcane, corn, cassava, and beet;
- CONAB [31] and Embrapa [38] provided the productivity and ethanol production performance from the investigated crops;
- Based on biomass performance data and [45, 51, 52] the energy matrix was developed.

The results are analyzed and compared with each other and with the results from sugarcane. Several aspects, including crop production, bio-ethanol productivity, generated energy and emissions were evaluated besides commenting on the social inclusion and food and energy securities.

4. Results and Discussion

According to the IBGE [26, 27], the agricultural area for family farming represents around 81 million hectares. The additional areas destined for the new agriculture products are 10, 20, 30, and 40 million ha, as mentioned before.

The crop production can be estimated by using the crop yield information from Table 4, multiplied by the respective area, and the results are presented in Table 6 and shown in Figure 7. No statistical validation was performed on the results.

Table 6 Family farming crop production.

Crop feedstock	Production (10^6 t) 10M ha	Production (10^6 t) 20M ha	Production (10^6 t) 30M ha	Production (10^6 t) 40M ha
Sugar beet	400	800	1200	1600
Cassava	350	700	1050	1400
Corn	145	290	435	580
Sugarcane	891	1782	2673	3564

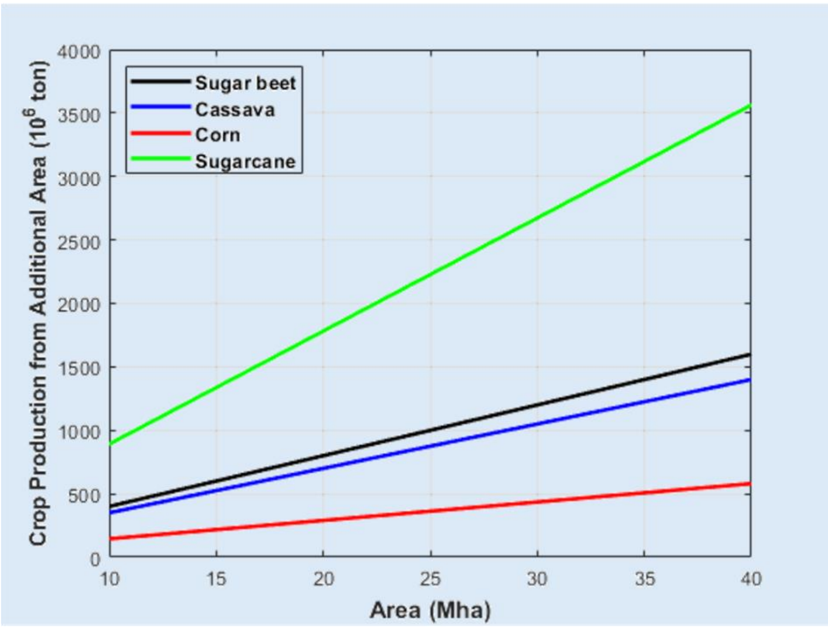

Figure 7 Crop production from the additional areas.

It is instructive to make a few comments on the results of Table 6 and Figure 7. The results show that sugarcane production is far more than the other products due to the fact that sugarcane is a crop used massively for sugar and ethanol production and is benefitted from the latest advanced plantation and collection technologies. Although sugar beet shows a high production it is not as popular crop in Brazil as sugarcane. Corn is a popular crop as food and also for variety of industrial and commercial applications. There are recent tendencies and some private initiatives to use corn for ethanol production. On the other hand, cassava has recently gained lots of attention because of its balanced contribution to food, industry, and energy. Land use for sugar beet and cassava is efficient since the plants are smaller in comparison to corn and sugarcane plants.

It is important to mention that climate conditions and soil type associated with irrigation and use or no use of fertilizer and its type have a strong influence on the production efficiency of the investigated crops. In Brazil, the fertility of the land and the weather conditions can significantly differ from one region to another, which is the reason why we could not assume analytical treatment for the sensitivity analysis of the results.

To estimate the potential of ethanol production from family farming in additional areas, one considers the ethanol yield from Table 5 and multiplies by the available area, and the results are presented in Table 7 and shown in Figure 8.

Table 7 Family farming ethanol production.

Crop feedstock	Production (10^6 m^3) 10M ha	Production (10^6 m^3) 20M ha	Production (10^6 m^3) 30M ha	Production (10^6 m^3) 40M ha
Sugar beet	100	200	300	400
Cassava	70	140	210	280
Corn	46	92	138	184
Sugarcane	108	216	324	432

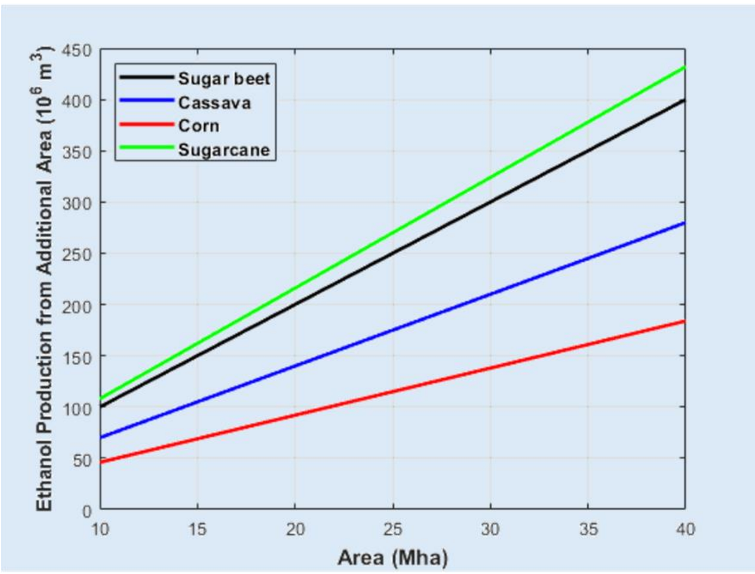

Figure 8 Ethanol production from the additional areas.

Currently, the principal supplies for food and meat for the internal market come from family farming production. Considering the additional agriculture area the sources for food will be increased and the agriculture wastes will also increase. In the present context, these wastes can be transformed into liquid, gaseous, and solid fuels according to the type of fuel needed and the treatment process used. Biodigestion can be used to generate biogas for local use and when enriched can produce biomethane, which has thermal characteristics similar to natural gas and can replace natural gas for transport and other applications. Also, biohydrogen can be obtained from agricultural wastes, although the results are still on a laboratory scale. Liquid fuels can be obtained by fermentation of agricultural wastes and can be used in transport systems. Solid fuels for heating and energy generation for domestic and commercial use can be obtained by densification of agriculture products in briquettes and pellets. Investigation are going on applying the concept of biorefinery for the production of chemical elements and other chemical products from agriculture wastes to replace similar products based on petroleum.

The crops have interesting nutritional values that could be implemented in daily diet. Table 8 presents some nutritional information for each 100 g of the selected crop.

Table 8 Nutritional properties of the crops.

Crop feedstock	Nutrient Energetic Value (kcal)	Nutrient Carbohydrates (g)	Productivity – Protein (g)	Productivity – C-Vitamin (mg)
Sugar beet	48.8	11.1	2.0	3.1
Cassava	151.4	36.2	1.1	16.5
Sugarcane	65.3	18.2	0.0	0.003
Corn	138.2	28.6	6.6	0.0
Sugarcane	65.3	18.2	0.0	0.003

The Food and Agriculture Organization of the United Nations [14] recommends the consumption of 2.000 to 2.400 kcal per day of nutrients divided by 55 to 65% carbohydrates and 10 to 30% protein. The C-vitamin quantity recommended is 45mg per day for people more than 19 years old, and this vitamin has many advantages for health.

Another analyzed aspect is the energy content of each crop. The energy content in the present study refers to the energy contained in a liter of ethanol produced. According to Monteiro [21] sugar beet presents a value of 23.90 GJ/m^3, and Salla et al. [51] and Pinho et al. [53] determined the cassava value as 23.40 GJ/m^3, Corn 23.60 GJ/m^3 and sugarcane 23.40 GJ/m^3. These values can be used to estimate the energy potential from the production of ethanol from the added areas as presented in Table 9 and shown in Figure 9.

Table 9 Energy contained in the ethanol from the investigated crops.

Crop feedstock	Contained energy (10^6 GJ) 10 M ha	Contained energy (10^6 GJ) 20 M ha	Contained energy (10^6 GJ) 30 M ha	Contained energy (10^6 GJ) 40 M ha
Sugar beet	2,390.0	4,780.0	7,170.0	9,560.0
Cassava	1,638.0	3,276.0	4,914.0	6,552.0
Corn	1,085.6	2,171.2	3,256.8	4,342.4
Sugarcane	2,527.2	5,054.4	7,581.6	10,108.8

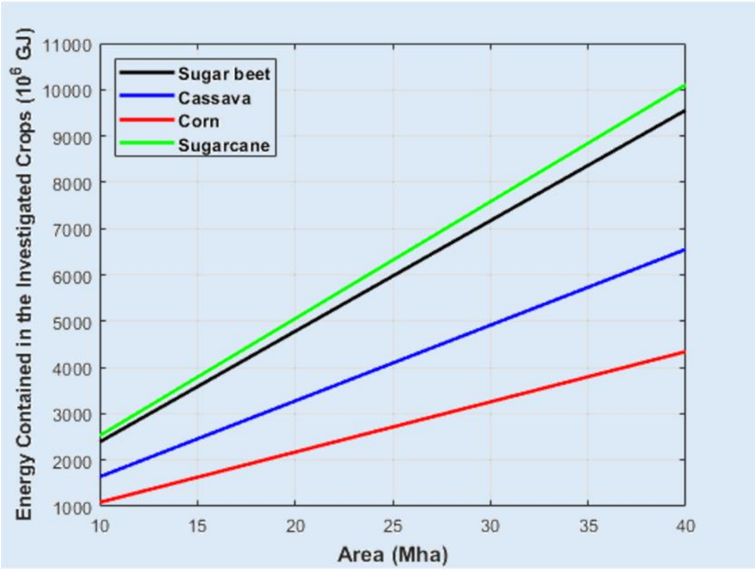

Figure 9 Energy contained in the ethanol from the investigated crops.

The results show that the amount of ethanol produced from sugarcane has the highest energy content followed by the amount of ethanol from sugar beet, while the amount of ethanol produced from corn has the lowest energy content and similarly cassava. The Sugarcane agriculture and the associated ethanol industry always received lots of attention and funds for the development and improving methods to enhance the productivity of crops and productivity of ethanol, equipment for plantation and collection of sugarcane, besides the efficient use of sub-products for energy generation and for use in second generation ethanol. These continuous efforts resulted in improving land productivity and enhancing the conversion processes for ethanol and sugar production.

Ethanol from corn, although it shows the lowest energy content, some industries started production of ethanol irrespective of its lower productivity in comparison with sugarcane. In the case of sugar beet and cassava, Brazil does not have projects to use these crops for ethanol production since this can cause interference between food and energy resources.

Regarding the total energy content of the produced ethanol, one can observe that the energy content of produced ethanol from sugarcane is the highest, followed by that from sugar beet, and the last is that from corn. Similar tendencies are found in the literature where ethanol from sugarcane shows total energy content of about 152 GJ/ha while corn and sugar beet show 2.5 GJ/ha and 15 GJ/ha, respectively.

The other important aspect to be measured is the emissions. Today, ethanol has an important contribution to reducing the CO_2 and decarbonization of the transport sector. According COP29, Brazil has plan is to reduce 53% of greenhouse emissions by 2030 [54].

Technical information on emissions occurring during the plantation period of the investigated crops are scarce in the literature. Also, emissions from the production of ethanol of these crops are also scarce except for the case of sugarcane. Consulting different sources it was possible to prepare Table 10, containing the total emissions of CO_2eq occurring during the plantation of the crops and production of ethanol. Observe that the results are from different regions in Brazil and different conditions for the production of ethanol. Table 10 is prepared based on available data from [55, 56].

Table 10 Ethanol total CO_2eq emission.

Crop feedstock	Ethanol total production emissions kg CO_2eq per liter of ethanol
Sugar beet	0.407
Cassava	1.031
Corn	1.696
Sugarcane	0.248

The emission from the additional areas can be estimated and the results are presented in Table 11 and shown in Figure 10.

Table 11 Total emissions due to ethanol production.

Crop feedstock	**Crop emission (10^6 t CO_2eq) Area of 10 M ha**	**Crop emission (10^6 t CO_2eq) Area of 20 M ha**	**Crop emission (10^6 t CO_2eq) Area of 30 M ha**	**Crop emission (10^6 t CO_2eq) Area of 40 M ha**
Sugar beet	40.7	81.40	122.1	162.8
Cassava	72.17	144.34	216.51	288.68
Corn	78.02	156.03	234.05	312.06
Sugarcane	26.78	53.57	80.35	107.15

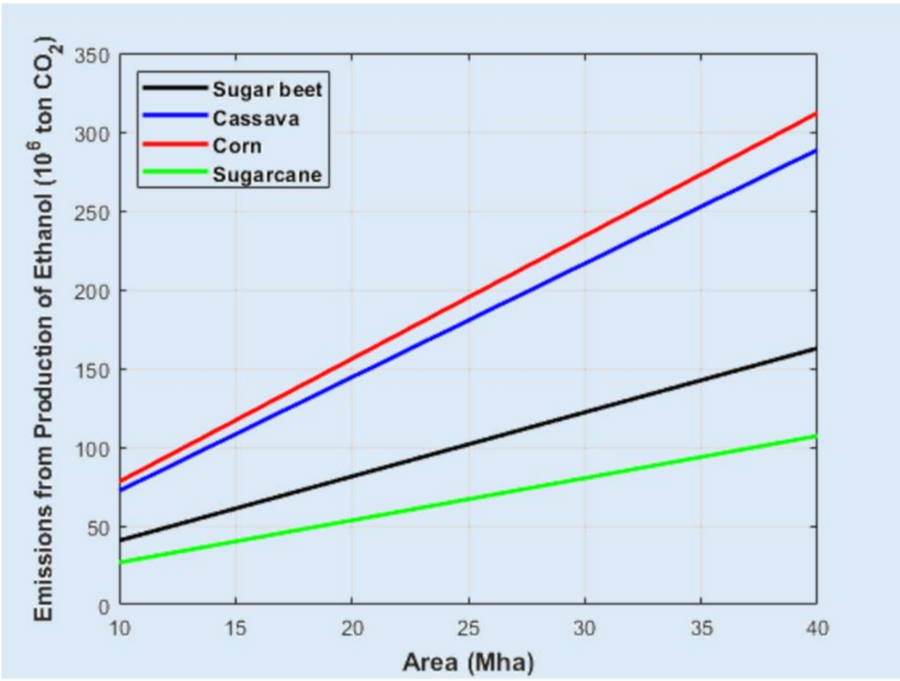

Figure 10 Total emissions from the production of ethanol.

The total emissions of CO_2 from the production of ethanol (kg CO_2eq/L) are composed of two main parts; the first is due to emissions during the period of the plantation until the harvest of the crop, while the second includes emissions due to the production process of ethanol. The sum of the two parts results in the total emissions generated to produce ethanol. The present results show that corn generates the highest amount of emissions in the production of ethanol of about 1.7 kg CO_2eq/L, while sugarcane produces 0.248 kg CO_2eq/L, the smallest of the investigated crops.

It is instructive to evaluate the agricultural and technological aspects related to ethanol production from the investigated crops. Sugar beet is a food product, and its excess can be used for the production of ethanol, while the wastes can be used as material for second-generation biofuel production or as animal feed. There is no accumulated “know how” in converting sugar beet, its peels and residues into ethanol. Pilot plants should be implemented for the family farmers to be trained, gain experience and efficiency in handling these installations. Cassava is a crop of multi used as food in nature, flour for diversified food and industrial applications. The cassava peels can be used as material for second-generation biofuel. Again, there is no accumulated experience on the use of cassava for ethanol production. However, pilot plants can be implemented for the family farmers to be trained and gain experience and know-how. Irrespective of these drawbacks, investments are made to increase cassava production. Cassava has wide use in food and many industrial applications, while cassava wastes and peels can be used for the production of second generation biofuels. Corn is a crop of potential use as food resource besides many applications including animal feed and industrial applications. In recent years, some agriculture companies started using corn for ethanol production for exportation. This experience can help the quick implementation on a big scale. On the other hand, using corn for producing ethanol can induce conflicts between food and energy resources.

5. Conclusions and Future Research Gaps

5.1 Conclusions

The increasing demands for energy and food urge us to explore renewable energy sources and sustainable food production. Although biofuel production can introduce potential risks to food security, these challenges can be mitigated by diversifying raw materials and promoting smallholder cultivation. Brazil's success in ethanol production from sugarcane is acknowledged, yet embracing alternative materials like sugar beet, cassava, and corn is strategically viable since they can attenuate the demand for food besides increasing biofuel offers.

Of the four scenarios for additional agricultural land to be transferred to Family farming, the scenario of 40 million hectares is empirically chosen as adequate to supplement biofuel demands and food needs and create food strategic reserves to control price oscillations, besides creating barriers against oscillations of the international food markets.

On a global scale, sugarcane dominates ethanol production of about 432 × 10^6 m^3. Though sugarcane excels in ethanol and sugar production, its limited utility as a food source is evident. Conversely, the other investigated raw materials can provide essential food support besides biofuel production.

The results show that the three investigated crop options are viable and interesting for balancing fuel and food production. The crop production of sugar beet is 1600 × 10^6 t and ethanol production of 400 × 10^6 m^3, while cassava produces 1400 × 10^6 t of crop with ethanol production of 280 × 10^6 m^3. Compared to sugarcane, sugar beet energy production is 9,560.0 × 10^6 MJ while cassava produces 6,552.0 × 10^6 MJ of energy. In terms of CO_2 emissions due to ethanol production, sugar beet produces 162.8 × 10^6 t CO_2 while cassava produces 288.68 × 10^6 t CO_2 and sugarcane produces 107.15 × 10^6 t CO_2.

Large-scale implementation of the presented solutions needs evaluating each crop from plantation to harvesting besides evaluating the challenges associated with the techniques to produce ethanol, which may differ from one crop to another. All this should be integrated in a long range development and implantation plan. A firm political will, long-term financial and human investments, infrastructure for both food and ethanol productions are necessary requirements to face the existing challenges.

The diverse sourcing of raw materials not only enriches the energy matrix but also fosters employment and income across regions. However, economic viability hinges on government incentives, production volume, decentralized production of crops and ethanol, farmer training, industrial returns, and production costs. The pursuit of energy transition and food security demands integrated sustainable solutions to address the world's global challenges.

5.2 Future Research Gaps

1. It is important to observe the need for infrastructure and technical support and public policies to help install and operate the cooperatives besides training and qualifying the associates and providing technical information on new agriculture advances.
2. Investigate the production of ethanol from glycerol to generate another biofuel from biodiesel industrial wastes.
3. Investigate the production of ethanol from cassava peels as material for second-generation biofuel.
4. More research and development are needed to implement the second-generation biofuels (bioethanol and biodiesel) based on food and agriculture wastes.
5. Funds for research and development to accelerate the third and fourth generation biodiesel and ethanol and enhance implementing production prototypes for operation tests.

Nomenclature

ANP	National Agency of Petroleum
GDP	Gross Domestic Product
SDG	sustainable development goal
Wb	wet base
IPCC	Intergovernmental Panel on Climate Change

Author Contributions

KI: Conceptualization, Writing - review & editing; **FL**: Methodology, Writing - original draft; **WB**: Writing - review & editing; **LS**: Soft ware, calculation and Writing - original draft; **JV**: Writing - original draft.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Tripathi AD, Mishra R, Maurya KK, Singh RB, Wilson DW. Estimates for world population and global food availability for global health. In: The role of functional food security in global health. Academic Press; 2019. pp. 3-24.
2. United Nations. World Population Prospects 2024 [Internet]. New York, NY: United Nations; 2024. Available from: https://population.un.org/wpp/.
3. Enciso SR, Fellmann T, Dominguez IP, Santini F. Abolishing biofuel policies: Possible impacts on agricultural price levels, price variability and global food security. Food Policy. 2016; 61: 9-26.
4. Koc Y, Kose O, Yagli H. Exergy analysis of a natural gas fuelled gas turbine based cogeneration cycle. Int J Exergy. 2019; 30: 103-125.
5. Neseli MA, Ozgener O, Ozgener L. Energy and exergy analysis of electricity generation from natural gas pressure reducing stations. Energy Convers Manag. 2015; 93: 109-120.
6. Pfeifer A, Herc L, Bjelić IB, Duić N. Flexibility index and decreasing the costs in energy systems with high share of renewable energy. Energy Convers Manag. 2021; 240: 114258.
7. Janda K, Kristoufek L, Zilberman D. Biofuels: Policies and impacts. Agric Econ. 2012; 58: 372-386.
8. IPCC. 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC; 2023; Item ID 17886.
9. Bao J, Zhang L, Song C, Zhang N, Guo M, Zhang X. Reduction of efficiency penalty for a natural gas combined cycle power plant with post-combustion CO_2 capture: Integration of liquid natural gas cold energy. Energy Convers Manag. 2019; 198: 111852.
10. Dutta K, Daverey A, Lin JG. Evolution retrospective for alternative fuels: First to fourth generation. Renew Energy. 2014; 69: 114-122.
11. Vignesh P, Kumar AR, Ganesh NS, Jayaseelan V, Sudhakar K. Biodiesel and green diesel generation: An overview. Oil Gas Sci Technol Rev IFP Energies Nouvelles. 2021; 76: 6.
12. Ong HC, Tiong YW, Goh BH, Gan YY, Mofijur M, Fattah IR, et al. Recent advances in biodiesel production from agricultural products and microalgae using ionic liquids: Opportunities and challenges. Energy Convers Manag. 2021; 228: 113647.
13. OECD-FAO. Agricultural Outlook 2021-2030 [Internet]. Rome, Italy: Food and Agriculture Organization of the United Nations; 2021. Available from: https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2021-2030_19428846-en.html.
14. FAO, IFAD, UNICEF, WFP and WHO. In brief to the state of food security and nutrition in the world 2024–Financing to end hunger, food insecurity and malnutrition in all its forms [Internet]. Rome, Italy: FAO; 2024. Available from: https://doi.org/10.4060/cd1276en.
15. World Bank, World health organization. Tracking universal health coverage: 2023 global monitoring report [Internet]. Geneva, Switzerland: World Health Organization; 2023. Available from: https://www.who.int/publications/i/item/9789240080379.
16. Aborisade B, Bach C. Assessing the pillars of sustainable food security. Eur Int J Sci Technol. 2014; 3: 117-125.
17. Abdulkadyrova MA, Dikinov AH, Tajmashanov HÈ, Shidaev LA, Shidaeva EA. Global food security problems in the modern world economy. Int J Environ Sci Educ. 2016; 11: 5320-5330.

18. Baer-Nawrocka A, Sadowski A. Food security and food self-sufficiency around the world. A typology of countries. PLoS One. 2019; 14: e0213448.
19. Mehariya S, Signorini A, Marone A, Rosa S. Simultaneous hydrogen and ethanol production from crude glycerol by a microbial consortium using fed-batch fermentation. Energies. 2023; 16: 4490.
20. Balat M, Balat H. Recent trends in global production and utilization of bio-ethanol fuel. Appl Energy. 2009; 86: 2273-2282.
21. Monteiro AF. Avaliação das potencialidades de produção de bioethanol em Portugal. Porto, Portugal: Universidade do Porto; 2011.
22. Awogbemi O, Von Kallon DV, Aigbodion VS. Trends in the development and utilization of agricultural wastes as heterogeneous catalyst for biodiesel production. J Energy Inst. 2021; 98: 244-258.
23. Tokarchuk D, Pryshliak N, Berezyuk S, Shynkovych A. Food security and biofuel production: Solving the dilemma on the example of Ukraine. Polityka Energetyczna. 2022; 25: 179-196.
24. Chilakamarry CR, Mimi Sakinah AM, Zularism AW, Khilji IA, Kumarasamy S. Glycerol waste to bio-ethanol: Optimization of fermentation parameters by the Taguchi method. J Chem. 2022; 2022: 4892992.
25. FAO, IFAD and WFP. The state of food insecurity in the world 2013: The multiple dimensions of food security [Internet]. Rome, Italy: Food and Agriculture Organization of the United Nations; 2013. Available from: https://www.fao.org/4/i3434e/i3434e.pdf.
26. IBGE. Censo agropecuário 2017: Agricultura Familiar [Internet]. Instituto Brasileiro de Geografia e Estatística; 2020. Available from: https://censoagro2017.ibge.gov.br/templates/censo_agro/resultadosagro/pdf/agricultura_familiar.pdf.
27. IBGE. Censo Agropecuário 2017 [Internet]. Instituto Brasileiro de Geografia e Estatística; 2020. Available from: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/21814-2017-censo-agropecuario.html?=&t=downloads.
28. Brasil/EPE. Balanço Energético Nacional ano base 2023. Rio de Janeiro, Brazil: Empresa de Pesquisa Energética; 2024.
29. CEPEA/Esalq/USP. Após Dois Trimestres Em Queda, Pib Do Agro Reage NO 3º TRI, E Recuo Esperado Para 2024 Diminuiu PARA 2.49% [Internet]. Piracicaba, Brazil: PIB do Agronegócio Brasileiro; 2023. Available from: https://cepea.esalq.usp.br/upload/kceditor/files/CT-PIB-AGRO_23.JAN.25.pdf.
30. Bustamante PM, Leite ME, Barbosa FD. A importância da agricultura familiar no âmbito do agronegócio brasileiro. Confluências. 2021; 23: 113-139.
31. Conab. Boletim da agricultura familiar [Internet]. Brasília, Brazil: Conab; 2022. Available from: https://www.conab.gov.br/.
32. OECD-FAO. Agricultural outlook 2023-2032 [Internet]. OECD-FAO; 2023. Available from: https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2023-2032_08801ab7-en.html.
33. IBGE. Levantamento Sistemático da Produção Agrícola de 2023 [Internet]. Instituto Brasileiro de Geografia e Estatística; 2024. Available from: https://sidra.ibge.gov.br/Tabela/1618.
34. de Oliveira MP, Rodrigues LH. How good are the models available for estimating sugar content in sugarcane? Eur J Agron. 2020; 113: 125992.

35. Wang Q, Che Y, Shao K, Zhu J, Wang R, Sui Y, et al. Estimation of sugar content in sugar beet root based on UAV multi-sensor data. Comput Electron Agric. 2022; 203: 107433.
36. El-Sheikh SR, Khaled KA, Enan SA. Evaluation of some sugar beet varieties under three harvesting dates. J Agric Chem Biotechnol. 2009; 34: 1559-1567.
37. Tivelli SW, Factor TL, Teramoto JR, Fabri EG, Moraes AD, Trani PE, et al. Beterraba: Do plantio à comercialização. Campinas, Brazil: Instituto Agronômico; 2011.
38. Embrapa. Produção rural por ano. Empresa Brasileira de Pesquisa Agropecuária [Internet]. Campinas, Brazil: Embrapa; 2021. Available from: https://www.embrapa.br/prosa-rural/por-ano-2021/.
39. IBGE. Produção de mandioca no Brasil em 2023 [Internet]. Instituto Brasileiro de Geografia e Estatística; 2024. Available from: https://www.ibge.gov.br/explica/producao-agropecuaria/mandioca/br.
40. Guimarães VF, Echer MM, Minami K. Métodos de produção de mudas, distribuição de matéria seca e produtividade de plantas beterraba. Hortic Bras. 2002; 20: 505-509.
41. Trani PE, Cantarella H, Tivelli SW. Produtividade de beterraba em função de doses de sulfato de amônio em cobertura. Hortic Bras. 2005; 23: 726-730.
42. Taco N. Tabela brasileira de composição de alimentos [Internet]. NEPA/Unicamp; 2011. Available from: https://www.gov.br/agricultura/pt-br/assuntos/inspecao/produtos-vegetal/legislacao-de-produtos-origem-vegetal/biblioteca-de-normas-vinhos-e-bebidas/tabela-brasileira-de-composicao-de-alimentos_taco_2011.pdf.
43. Sangoi L, Schmitt A, Durli MM, Leolato LS, Coelho AE, Kuneski HF, et al. Estratégias de manejo do arranjo de plantas visando otimizar a produtividade de grãos do milho. Rev Bras Milho Sorgo. 2019; 18: 47-60.
44. Paes MC. Aspectos Físicos, Químicos e Tecnológicos do Grão de Milho [Internet]. Sete Lagoas, Brazil: Embrapa Milho e Sorgo; 2006. Available from: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/489376.
45. Salla DA. Análise energética de sistemas de produção de ethanol de mandioca, cana-de-açúcar e milho. Rev Eng Agríc. 2010; 25: 32-53.
46. Veiga JPS, Valle TL, Feltran JC, Bizzo WA. Characterization and productivity of cassava waste and its use as an energy source. Renew Energy. 2016; 93: 691-699.
47. Silva RM, Fernandes AM, Leonel M, Pelvine RA, Figueiredo RT, Rangel MA, et al. Measurement of Dry Matter and Starch in Modern Cassava Genotypes during Long Harvest Cycles. Horticulturae. 2023; 9: 733.
48. FAO. Crops and livestock products [Internet]. Roma, Italy: Food and Agriculture Organization of the United Nations; 2021. Available from: https://www.fao.org/Faostat/En/#data/QCL2021/.
49. FAO. World food agriculture [Internet]. Roma, Italy: Food and Agriculture Organization of the United Nations; 2023. Available from: https://reliefweb.int/report/world/fao-statistical-yearbook-2023-world-food-and-agriculture/.
50. ANP. Mapa dinâmico - Produtores de ethanol [Internet]. Agencia Nacional de Petróleo; 2024. Available from: https://www.gov.br/pt-br/paineis-dinamicos-da-anp.
51. Salla DA, Furlaneto FP, Cabello C, Kanthack RA. Avaliação energética da produção de etanol utilizando como matéria-prima a cana-de-açúcar. Ciênc Rural. 2009; 39: 2516-2520.
52. Nguyen TLT, Gheewala HS, Garivait S. Full chain energy analysis of fuel ethanol from cassava

in Thailand. Environ Sci Technol. 2007; 41: 4135-4142.
53. Pinho MJ, Zanon R, Meirelles B, Ribeiro P. Inclusão produtiva rural: A trajetória do BNDES Fundo Social de 2009 a 2020. Banco Nacional de Desenvolvimento. Rev BNDES. 2021; 28: 133-188.
54. EBC. Brazil's emissions trajectory and reduction goal for 2035 [Internet]. Empresa Brasil de Comunicação; 2024. Available from: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2024/11/meta-da-ndc-brasileira-para-2035-acelera-velocidade-de-reducao-de-emissoes.
55. Numjuncharoen T, Papong S, Malakul P, Mungcharoen T. Life-cycle GHG emissions of cassava-based bioethanol production. Energy Procedia. 2015; 7: 265-271.
56. Manochio C. Produção de bioetanol de cana-de-açúcar, milho e beterraba: Uma comparação dos indicadores tecnológicos, ambientais e econômicos. Universitária, MG: Universidade Federal de Alfenas, Campus Poços de Caldas/MG; 2014.