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Review
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POTENTIAL BIOENERGY CROPS: SWEET SORGHUM AND GLOBE ARTICHOKE

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Abstract: The growing international demand for petroleum-based fuel and the related environmental issues, such as greenhouse gas emissions, global warming, and changes in the climate, have redirected global focus toward the development of sustainable, eco-friendly, and renewable fuels derived from energy crops. The production of biofuel utilizing fast-growing and very effective bioenergy crops is becoming a dependable substitute for fossil fuels. Bioenergy crops refer to specific plants that are cultivated and managed at reduced expenses for the purpose of producing biofuels. Among these, globe artichoke and sweet sorghum are significant bioenergy crops that can expedite the shift towards a low-carbon economy. Both plants are important crops that serve multiple purposes as food, animal feed, and bioenergy sources. Moreover, they are highly adaptable to harsh conditions. The potential for ethanol production from sweet sorghum is a minimum of 6000 L per hectare. Globe artichoke, on the other hand, has high biomass and energy production even with limited external management sources. These traits make them highly desirable as bioenergy plants. This review demonstrates the potential of global artichoke and sweet sorghum as bioenergy sources. A comprehensive understanding of the bioenergy potential of globe artichoke and sweet sorghum will better allow us to exploit these crops.

Keywords: Biomass, *Cynara cardunculus*, Fossil fuels, *Sorghum bicolor*

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1. Introduction

By 2050, there will probably be 9.1 billion people on the planet, 550 parts per million of CO_2 in the atmosphere, 60 parts per billion of ozone, a 2 °C rise in temperature (Jaggard et al., 2010), and fossil fuel resources will likely be depleted (Saidur et al., 2011). This suggests that action needs to be taken to save the environment and enhance the production of food and energy to fulfill the requirements of the growing population.

Fossil fuels which provide our current energy needs, are considered to be among the most important resources on Earth. In other words, about fifty-eight percent of the fuels utilized for energy are derived from fossil fuels, which make up 80% of the fuel supply (Escobar et al., 2009; Gaurav et al., 2017). However, in recent years, there has been an extraordinary and uncontrolled use of fossil fuels worldwide. Using these fuels increases the amount of dangerous chemicals in the atmosphere, such as nitrogen oxide, carbon dioxide, and greenhouse gases. For instance, the emission of greenhouse gases by coal, such as carbon dioxide, particle ash, and substances containing sulfur, causes acidity in the soil. Nuclear fission produces enormous amounts of infrastructure-related energy that are detrimental to both the ecosystem and human health (Gresshoff et al., 2017; Yadav et al., 2019). Because fossil fuels are used excessively, it has been found that the sources of oil reserves and fossil fuels are major contributors to air pollution and harmful gas emissions. This in turn causes changes in the climate and biodiversity brought on by globalization, among other effects such as melting glaciers and rising water levels (Shweta et al., 2024). Long-term environmental effects linked to the usage of fossil fuels include land degradation and desertification of rich soils (Karp and Shield, 2008; Yadav et al., 2019). The consequences of the explosion in the use of fossil fuels are now evident in the form of diseases connected to pollution in the environment, changing the climate, and excessive precipitation.

With the growing worldwide worries about climate change, the relationship between bioenergy and agriculture has become increasingly important and demands careful investigation (Bibri et al., 2024; Soyombo et al., 2024). Collaborative efforts are facilitated by the fact that the production of biofuel and the storage of carbon in bioenergy crops both contribute to the overall objectives of sustainable agriculture (Welfle and Röder, 2022; Soyombo et al., 2024). The use of organic resources to produce bioenergy presents a promising substitute for traditional fossil fuels that are low-carbon and renewable. Sustainable agriculture posits that to fulfill the increasing demands of an expanding global population, farming techniques should be both resource-efficient and ecologically conscious (Athuman, 2023; Soyombo et al., 2024).

Conventional fuels continue to be the primary energy source in a large number of countries. Due to the widespread recognition of the detrimental effects of using fossil fuels, efforts have been made to find alternate fuel sources. A number of countries have switched from using non-renewable to using renewable energy alternatives as their top concern when it comes to energy supply. Only a restricted amount of energy sources, nevertheless, are environmentally friendly and sustainable. Using "bioenergy crops" to generate energy is one such viable option with promising long-term results (Yadav et al., 2019).

Bioenergy crops acquire their energy from biomass that is derived from both plants and animals. Crop products used in bioenergy production include ethanol, biodiesel, biogas, and others (Yuan et al., 2008). Increased soil carbon, decreased greenhouse gas emissions, decreased soil erosion, increased transpiration, and the potential to produce heat and power are all benefits of bioenergy crops (Wang et al., 2012; Kim et al., 2013; Yadav et al., 2019). The phytoremediation of soil polluted with heavy metals is another benefit of bioenergy crops (Barbosa et al., 2015). Crops grown for bioenergy on huge scales may also benefit wildlife.

Bioenergy crops are gaining global interest due to their renewable and environmentally favorable characteristics. Nevertheless, the global market mostly utilizes bioenergy crops for food purposes, which therefore raises concerns over food safety when used for energy production. In addition to using bioenergy plants as food, it is very important to use their biomass as a source of bioenergy. There are a lot of potential bio-energy plants of this type. This review describes the features of potential bioenergy crops, particularly globe artichoke and sweet sorghum.

2. Bioenergy Crop Types

Traditional bioenergy crops have the added benefit of reducing global climate change, which might enhance the production of food as well as fodder. The five primary categories into which they are divided are first-, second-, and third-generation crops, specialized energy crops, and halophytes (Figure 1).

Although the energy from specialized bioenergy crops is now minimal, it is anticipated that in coming years, it will account for a significant portion of the overall biomass potential. Selecting the best bioenergy crop to cultivate is a difficult decision that depends on several aspects such as, soil and environmental conditions, market accessibility, transporting and harvesting challenges, and more. Six main categories may be used to group bioenergy crops according to their structural makeup, conversion method, and bioenergy utilization (Karp and Shield, 2008);

1. Using second-generation crop/fuel chains, woody lignocellulosic plants such as poplar, willow, and eucalyptus may be used to produce wood chips, pellets, or bioethanol*;
2. Using a second-generation crop/fuel chain, herbaceous lignocellulosic plants such as miscanthus, switchgrass, Cynara, fiber sorghum, and kenaf can be used to produce agro-pellets, biogas, or bioethanol;
3. Oil crops such as sunflower, soybean, rapeseed, and oil palm are used to produce agro-pellets utilizing crop leftovers and biodiesel based on a first-generation crop/fuel chain;
4. Depending on a first- or second-generation crop/fuel chain, sugar crops including sugarcane, sweet sorghum, and sugar beet are used to produce bioethanol;
5. Utilizing agricultural leftovers and first-generation crop/fuel cycles, starch crops such as wheat, rye, triticale, and maize are used to produce agro-pellets and bioethanol;
6. Biogas may be produced for fuel, heat, or power by processing Leguminous plants and grasses with manure or waste.

*Biofuels classified as a first, second, or third generation are fuel/crop cycles that rely on current, emerging, and future conversion technologies, in that order.

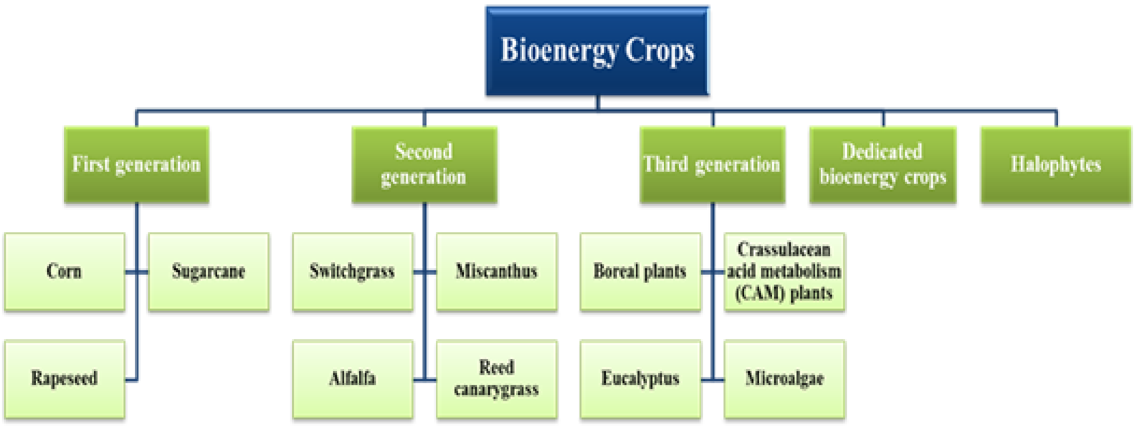

Figure 1. Bioenergy crop types (Adapted from Yadav et al., 2019).

The main energy crops grown worldwide are sugarcane, oil palm, rapeseed, and to a much lesser extent, miscanthus, poplar, willow, and eucalyptus. Now employed for both solid and gaseous biofuel manufacturing, miscanthus, willow, and poplar are the top three crops in the EU-27 for biodiesel production, with rapeseed and sunflower coming in second and third respectively (Christou et al., 2010).

Certain energy crops, like Cynara cardunculus and Sorghum bicolor, have several uses and purposes. Indeed, many other crops, including globe artichoke and sweet sorghum are being extensively researched currently (Archontoulis, 2011; Gominho et al., 2011; Olweny et al., 2013).

3. Globe Artichoke

The Asteraceae species *Cynara cardunculus* L. (Figure 2) comprises both the wild (var. sylvestris) and cultivated cardoon (var. altilis), in addition to the well-known edible globe artichoke (var. scolymus). It is a Mediterranean-native perennial C3 species that avoids the warmest and driest period of the year by starting its growth cycle in the fall and finishing it in the early summer (Sonnante et al., 2007, Mauro et al., 2012, Pesce et al., 2017). The 'Cynara' genus, which includes the globe artichoke [*Cynara cardunculus* var. scolymus (L.)], has a history dating back to the Ice Age. It is thought to be endemic to the Mediterranean region, which includes Southern Europe and Northwest Africa. Its predecessor is the thistle. During this time, wild artichokes, or "cardoons," were found across the Mediterranean region, extending from the southern portion of the basin to the Sahara. Towards the end of the ice age, they also reached the eastern and western regions of the Mediterranean, where they are now widely cultivated (Ciancolini, 2012). Nowadays, an important crop and source of alternative medicine, globe artichoke has been cultivated extensively, particularly in several countries around the Mediterranean.

Cynara is a perennial C3 plant with yearly cycles that may be utilized to produce bioethanol (lignocellulosic biomass), biodiesel (from seeds), or combined heat and power. Cynara is harvested dry in the summer, with the production of biomass ranging from 6 to 30 t dry matter ha-1 y-1, and cultivated as rainfed during the fall, winter, and spring seasons. *Cynara cardunculus* has been recognized as one of the number potential candidate species for bioenergy manufacturing in the Mediterranean region since it meets a variety of cropping approaches (the length of the growing season and whether irrigation is used or not, etc.). Also, previous studies have demonstrated favorable findings in regard to their capacity for production (Archontoulis, 2011).

3.1. Agronomic Characteristics of Globe Artichoke as a Bioenergy Feedstock

The morphology of the perennial herbaceous plant artichokes is examined in two sections. Its above-ground parts (shoot, leaves, and flowers) are annual and can grow up to 1 m tall and cover a 1 m^2 area. Depending on the variety, the rosette-shaped leaves can have segmented or unsegmented structures. A growth tip is located where the leaves merge, and the flower stem grows when the air temperature is between 13 and 17 °C (Ekbiç, 2005).

It has been cultivated for its immature blooms or heads, and because of the high bioactive content of its body and leaves -which are still regarded as waste- it has lately started to be employed in a variety of sectors, particularly in medicines.

Figure 2. *Cynara cardunculus* var. *scolymus* (L.).

The heads (inner bracts and 'heart') and the base of the flowers are the components of the perennial globe artichoke plant that are consumed. Nonetheless, outer bract leaves on the heads, stem, and leaves are regarded as non-food components (Ruiz-Aceituno et al., 2016). Although it fluctuates based on genotype and harvest time variances, the ratio of edible sections to the entire plant is generally recognized to be between 35 and 55 percent (Abu-Reidah et al., 2013).

The primary use of Cynara as a crop for energy is in the production of solid biofuel. The following crop attributes lend support to this application: a high biomass productivity with a comparatively little amount of crop input conditions of a Mediterranean climate, low biomass moisture content at harvest, mostly lignocellulosic biomass composition, and a high heating value. From a botanical standpoint, Cynara and sunflowers are related. Both produce oil fruits, which are commonly referred to as "seeds."

The following characteristics also indicate Cynara's potential as an oil crop: heating value, fatty acid composition, seed yield, and seed oil content (Fernandez et al., 2006). Within the scope of a European project, the potential of Cynara biomass for the production of paper pulp was investigated and demonstrated; the hemicellulose, cellulose, and lignin contents of the various plant sections of a Cynara crop harvested at the end of the cycle (summer) and evaluated. Additionally, a number of studies have shown the potential of the Cynara crop for producing green feed (Fernandez et al., 2006).

3.2. Production of Globe Artichoke

It is a herbaceous perennial plant that can withstand droughts and is easily grown from seed, which has significant benefits for crop management. Because it can be grown without irrigation (rainfed), it is especially suited to Mediterranean climates, where water is the primary problem restricting productivity (Rana et al., 2016). The globe artichoke is grown for its juvenile inflorescence, which can be eaten raw or cooked (Pesce et al., 2017). The germination of seeds, which typically occurs in early autumn, initiates the first growth cycle of artichoke. After the first two new cotyledons appear, a number of leaves quickly sprout and eventually form a leaf rosette. Typically, the leaf rosette grows quite slowly but steadily. The plant experiences winter and early spring when it is in the rosette stage. The plant produces a leaf-branched flower scape with many heads by late April. The fruits ripen following full bloom and flower fertilization, and the aerial biomass eventually dries up in the summer.

Perennating buds on the basal plant portion sprout and a new development cycle begins when the weather gets milder. It may continue for a few years. There have been reports of this annual growth cycle succession lasting more than 15 years (Fernandez et al., 2006).

In the last twenty years, rainfed countries in Mediterranean climates have come to regard the cultivated cardoon as a possible energy crop. Since both wild and cultivated cardoon forms present a significant amount of biomass regardless of being given very little input, they have been suggested as potential bioenergy crops since they may be grown on land that isn't often utilized for cropping (Mauromicale et al., 2014; Mauro et al., 2015). The biomass may be burned directly to provide energy, and the oil that collects in the achenes can be used as a fuel to make biodiesel (Encinar et al., 2002; Fernandez et al., 2006; Pesce et al., 2017). On the other hand, the cardoon biomass, including its high carbohydrate and low lignin concentration, offers the potential for fermentation to produce ethanol or biomethane (Cotana et al., 2015; Fernandes et al., 2015; Pesce et al., 2017); currently, the majority of this is achieved using maize silage, while triticale and bread wheat biomass are also used to a lesser extent (Dressler et al., 2012; Pesce et al., 2017). This crop's strong biomass and energy production under minimal external management energy sources are what draw attention to it (Ierna et al., 2012a; Acquadro et al., 2013; Mauromicale et al., 2014). The exceptional adaptation of Cynara to the Mediterranean climate indicates this feature. This includes the ability to uptake nutrients from deep soil layers, photosynthesize during the winter, and maintain an ideal equilibrium between the stages of the plant's life cycle and variations in the Mediterranean climate. In fact, the extremely deep root system makes it possible to explore the soil at a deeper level and to take water and nutrients that have accumulated throughout the soil profile (Ierna et al., 2012b; Mauromicale et al., 2014).

4. Sweet Sorghum

Sorghum bicolor (L.) Moench belongs to the Andropogoneae tribe, which is a part of the panicoideae tribe of the grass family, poaceae (Kellogg, 2013). The earliest cultivated sorghums were discovered in Neolithic populations in Sudan about the fourth millennium BC (Winchell et al., 2017). Domesticated sorghum, originating from its earliest predecessor in Africa, was spread worldwide via numerous methods, with trading routes being the most prevalent (Ananda et al., 2020). *Sorghum bicolor* (L.) Moench, commonly referred to as sorghum, is classified as one of the most prominent five cereal crops globally (Venkateswaran et al., 2014). It has a crucial function in the production of food worldwide and serves as the main source of sustenance for billions of people (Mace et al., 2009). Sorghum is a versatile crop that is used for several purposes, including grain, sweet, fodder, and broomcorn (Ananda et al., 2020). In addition, it functions as a fuel source, providing bioethanol. It is a crucial staple crop in arid and semi-arid areas worldwide, whereas in wealthy countries it is mostly cultivated for animal feed and forage purposes (Venkateswaran et al., 2019).

Sweet sorghum is a C4 plant species characterized by its broad, flat leaves and a rounded or oval head filled with mature grains. This is a short-day plant, and its blooming process is accelerated by shorter days and longer nights. Sorghum grows in arid and semi-arid regions, exhibiting a temperature range of 12–37 °C, with its optimal range being 32–34 °C (Rao et al., 2009). The ideal conditions for optimal growth and maximum stem juice yield are loam and sandy loam soils with soil temperatures above 18°C and pH levels around 5.8 (Mask and Morris, 1991).

4.1. Agronomic Characteristics as a Bioenergy Feedstock

As a bioenergy crop, sweet sorghum cultivars must have many desirable traits (Appiah-Nkansah et al., 2019):

1. The sweet sorghum cultivars have a high amount of biomass production.
2. The stalk of this plant is thick and can withstand.
3. The juice extracted from cultivars has a high content of total soluble brix.
4. These cultivars have a high percentage of extractable juice.

Sweet sorghum refers to sorghum cultivars that produce juice which comprises up 78% of the total plant biomass. This juice contains 15 to 23% fermentable sugar, which mostly consists of sucrose (70–80%), along with fructose and glucose (Appiah-Nkansah et al., 2019) that can be easily converted into ethanol (Vinutha et al., 2014).

In the past, sweet sorghum juice had been utilized as a natural sweetening agent by concentrating it into a syrup. Additional research has shown that sweet sorghum juice may be transformed into granulated sugars, granul syrups, and jaggery. Furthermore, it can serve as a base material for the production of hydrogen and methane (Antonopoulou et al., 2008). The utilization of sweet sorghum as a substrate for ethanol production emerged in the late 1970s (Umakanth et al., 2019) and is currently gaining attention due to its notable characteristics, including its high productivity, strong resistance to stress, and ability to easily integrate into existing agricultural systems as a bioenergy crop.

Furthermore, the requirements for desirable traits in sweet sorghum, such as tolerance to environmental and biological stresses and high grain yield, differ across different production systems. After extracting the juice, the remaining bagasse, which is a dry fibrous material made of lignocellulose, can be utilized for various purposes including paper manufacturing, animal feed, production of cellulosic ethanol (Appiah-Nkansah et al., 2019).

4.2. Production of Sweet Sorghum

Sweet sorghum has better drought tolerance compared to the majority of other C4 grasses, making it a highly efficient crop with minimal resource requirements. The productivity in a particular region is determined by climatic conditions, soil type, and agronomic methods (Rooney et al., 2007). For instance, research performed in central Iowa, United States, suggested planting sweet sorghum early to produce a biomass production of 26 to 29 tons per hectare, with a theoretical ethanol potential of 14,500 liters per hectare (Khawaja et al., 2014). In India, the cultivation of sweet sorghum is suggested during the rainy season, post-rainy season, and summer season, contingent upon the accessibility of water resources (Appiah-Nkansah et al., 2019).

The cultivation of sweet sorghum is possible in several soil types, but the most productive soils for this crop is well-drained and have a well-structured composition, namely red or black clay loam soils (Reddy et al., 2005). Sweet sorghum needs a well-balanced application of fertilizers in order to produce a high-yielding crop. The specific quantities of fertilizers required depend on the existing levels of nitrogen (N), phosphorus (P), and potassium (K) in the soil profile. While sweet sorghum constitutes a crop that can withstand drought conditions, the availability of water also has a substantial impact on its yield.

Early planting often enhances sugar yield and had a substantial positive impact on agricultural productivity (Teetor et al. 2011). Moreover, it has been shown that the yield increases when radiation levels rise during the reproductive period. For example, Ricaud and Arenneaux (1990) found that the average stalk yields in Louisiana were 56 and 49 Mg ha-1 when planting was carried out on 26 April and 25 May, respectively, across several cultivars.

The stalk sugar content varies depending on the cultivar and the growing stage of the plant. Early cultivars often have the highest concentration of sugar in their stalks just before they blossom, while late-maturing cultivars with longer growing seasons continue to accumulate sugar in their stalks until they reach maturity (Shukla et al., 2017). According to Lingl (1987) and Regassa and Wortmann (2014), the sugar concentration in the stalk is often at its lowest during the boot stage and reaches its maximum level during the soft dough stage. Ricaud et al. (1979) discovered that the sugar level in stalks varied from 8.3% to 14.0% during the blooming stage and from 12.8% to 16.6% during the soft dough stage. The optimal development stage for harvesting sweet sorghum might vary depending on the cultivars, ranging from the early milk stage to the hard dough stage (Oyier, et al., 2017).

The potential for ethanol production from sweet sorghum is 6000 L per hectare, with an energy yield on investment of more than three units each unit invested. Sweet sorghum has a Brix percentage ranging from 13 to 24, with a juice sucrose concentration of 7.2 to 15.5%. It yields a total stalk sugar yield of 12 mg ha-1, a fresh stalk yield of 24 to 120 mg ha-1, and a biomass yield of 36 to 140 t ha-1 (Regassa and Wortmann, 2014).

5. Conclusion

The urgent need to combat climate change motivates the investigation of potential synergies between sustainable agriculture and bioenergy. The scientific community is interested in the idea of bioenergy crops because of their eco-friendliness and renewability. By providing a competitive substitute for traditional fossil fuels, bioenergy from renewable organic substances helps to lower the emissions of greenhouse gases. Globe artichoke and sweet sorghum are perfectly in line with the goals of sustainable agriculture, which stresses eco-friendly methods to lessen the effects of climate change. With these plants, by recognizing and utilizing the synergistic impact of sustainable agriculture and bioenergy, we may shift to a low-carbon economy and make major progress against climate change.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	B.G.	T.Ö.K.
C	50	50
D	50	50
S	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50

C=Concept, D= design, S= supervision, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declare that there is no conflict of interest.

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