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Ethnobotanical Study on Some Tree Species Used as Bioenergy, Sudan

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Ethnobotanical Study on Some Tree Species Used as Bioenergy, Sudan

Written by in order to obtain Doctoral (PhD) degree:

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ABBREVIATIONS

BEFS Bioenergy and Food Security
BEFSCI Bioenergy and Food Security Criteria and Indicators
BERC Biomass Energy Resource Centre
CO_2 Carbon dioxide
DLUC Direct Land Use Change
ELCA Energy Life Cycle Analysis
FSP Fibre Saturation Point
FL Fidelity level
FIC Factor Informants Consensus
FNC Forest National Corporation, Sudan
FER Fossil Energy Ratio
GHG Greenhouse Gas
HHV High Heat Value
IPCC Intergovernmental Panel on Climate Change
ICS Improved Cook Stoves
ILUC Indirect Land Use Change
IDPs Internally Displaced People
LHV Low Heat Value
LPG Liquefied Petroleum Gas
MC Moisture Content
MTOE Million Tons of Oil Equivalent
N_2O Nitrous Oxide
NGOs Non-governmental Organizations
NER Net Energy Ratio
RCI Relative Cultural Significance Indices
SRC Short Rotation Coppice
UV Use Value

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ABSTRACT

The growing demand for renewable and environmentally friendly energy sources has prompted many countries, including Africa, to focus on biomass-based energy production. In Sudan, where liquefied petroleum gas distribution is limited in rural areas and towns, biomass serves as the primary energy source for domestic purposes such as cooking, heating, bakeries, and brick production. This study employed ethnobotanical methods to gather knowledge from local communities regarding the desired properties of biomass resources used for energy production, aiming to document these findings scientifically. By incorporating consumer preferences, this research offers valuable insights for decision-makers in identifying suitable and preferred biomass species. A stratified sampling technique was employed, and a comprehensive questionnaire was designed to investigate various aspects related to consumer preferences and biomass characteristics for energy utilization. The survey findings consistently highlighted sustainable combustion as a crucial characteristic desired in biomass resources within the study area. Among the local tree species examined, *Acacia mellifera* and *Acacia nilotica* were identified as the most important energy tree species. Furthermore, *Acacia seyal* emerged as the preferred species for domestic use, as indicated by survey respondents. For bakeries, *Acacia mellifera* was the most preferred species, while *Acacia nilotica* was favoured by brickmakers. Notably, the study revealed a significant perception among respondents regarding the negative correlation between increasing biomass fuel consumption for energy purposes and the decline of forest areas in the study area. Additionally, the findings indicated that family size had a positive and statistically significant impact on biomass fuel consumption.

To validate and expand upon the study's results, further research and laboratory testing are recommended to assess the tree characteristics of selected species in energy plantations and agroforestry programs in Sudan. Such investigations would contribute to confirming the suitability of identified species for biomass-based energy production and inform sustainable energy strategies in the region.

CHAPTER 1. INTRODUCTION

The sustainable and environmentally friendly nature of biomass makes it a viable answer to global energy problems in the face of environmental challenges, increasing energy demand and decreasing availability of other energy sources (Solarin et al., 2018). Several countries, especially in Africa, are increasing their biomass production for energy generation. About 87% of primary energy consumption in Sudan comes from biomass as reported by (Galal, 1997). Biomass serves as the predominant source of energy in rural and urban parts of Sudan that have limited access to LPG. It is used for a range of household purposes including cooking, heating, bakeries, and brick making. The United Nations Environment Program (UNEP, 2008) has emphasized that the increasing demand for energy in Sudan, caused by population growth and internally displaced people, has led to overexploitation of forest resources and a decline in species used for energy purposes.

The transition from conventional species with favourable energy properties to novel species with poorer energy quality poses a risk to the latter and therefore requires the restoration of degraded species. Before selecting species as a biomass feedstock source, it is important to prioritize restoration as it has a significant impact on the different fuel qualities (Neves et al., 2011; Jacob-lopes et al., 2019). Assessing the quality of biomass is crucial for its practical use, as combustion is the most important process for converting biomass fuel into electricity in Sudan. It is important to focus on key characteristics such as moisture content, density, and ash content. It is important to keep the moisture content below 20% to minimize problems related to transportation, storage, and energy value. Experts (Meincken et al., 2014) recommend the high density of the biomass as it is favourably linked to the calorific value. In addition, reducing the ash content is crucial as it has an unfavourable relationship with the calorific value (Ahmed, 2021).

Careful selection of species with efficient energy qualities and sustainable biomass supply is crucial, especially when considering government programs for energy plantations. To meet the increasing demand for biomass feedstock, it is imperative to use alternative sustainable methods. In this research, ethnobotanical techniques were used to collect information from local people about the desired characteristics of plants for local energy production and to systematically record these discoveries using scientific means. Therefore, the research uses these findings to make suggestions.

1.2 Research objectives

The objective of this research is to conduct an ethnobotanical study focusing on tree species used as bioenergy sources in Sudan. The study aims to explore and document the traditional knowledge and practices associated with the utilization of specific tree species for bioenergy purposes in the region. By achieving this objective, the research intends to contribute to the understanding of the sustainable use of bioenergy resources, while also promoting the conservation and management of tree species in Sudan. Specifically, the following sub-objectives will be pursued:

I. Provide ethnobotanical information on preferred local energy tree species based on biomass characteristics.
II. Identify and document the tree species commonly used for bioenergy purposes in the study area, considering their traditional and scientific names.
III. Investigate the ethnobotanical knowledge and practices related to the collection, and utilization of these tree species for bioenergy among local communities in the study area.
IV. Evaluate the sustainability of the current bioenergy practices and their potential implications for the long-term conservation of tree species and forest ecosystem in the study area.
V. Provide recommendations for the development of effective policies and conservation strategies that support the sustainable utilization of tree species for bioenergy in the study area, considering the perspectives and needs of local communities and the broader environmental context.

1.3 Research question

This study motivated by the following research questions:

I. What are the tree species commonly utilized for bioenergy purposes in the study area?
II. What are the traditional knowledge and practices associated with the selection of tree species for bioenergy in the study area?

III. What are the preferred tree species for different bioenergy applications (e.g., cooking, heating, lighting, baking, and brickmaking etc) among local communities in study area?

IV. How do local communities in study area perceive the sustainability and availability of tree species used as bioenergy sources?

V. What are the potential alternative bioenergy sources that could be explored in study area to reduce the dependence on traditional tree species?

VI. What policy and management strategies could be implemented to promote sustainable utilization and conservation of tree species used as bioenergy sources in study area?

VII. How can the findings of this ethnobotanical study be applied to inform conservation strategies, resource management plans, and sustainable development initiatives related to bioenergy utilization in study area?

1.4 Significant of research

The significance of research is multi-faceted and encompasses various domains, including environmental, socio-cultural, and policy-related aspects. Here are some significant aspects of this research:

I. Conservation and sustainable use of tree species: The study contributes to the conservation and sustainable use of tree species in the study area. By documenting the knowledge of local communities, the research identifies the tree species that are commonly used as bioenergy sources. This information can be used to develop conservation strategies and sustainable management practices to ensure the long-term availability of these species.

II. Energy security and rural livelihoods: Bioenergy plays a crucial role in meeting the energy needs of rural communities, particularly in developing regions. Understanding the tree species utilized for bioenergy can help in assessing the energy security situation and identifying potential strategies for improving access to reliable and sustainable energy sources. This research can contribute to the formulation of policies and interventions that enhance rural livelihoods by addressing energy poverty.

III. Climate change mitigation and adaptation: Bioenergy derived from tree species can play a role in mitigating climate change by reducing dependence on fossil fuels. This research provides insights into the tree species with bioenergy potential, enabling the identification of suitable species for afforestation and reforestation programs. Such initiatives can contribute to carbon sequestration, ecosystem restoration, and climate change adaptation strategies at local and regional levels.

IV. Policy development and decision making: The findings of this ethnobotanical study can inform policy development and decision-making processes related to bioenergy and natural resource management. The research can provide evidence-based recommendations for sustainable bioenergy production, land-use planning, and conservation measures. Policymakers and stakeholders can utilize these recommendations to formulate effective policies, guidelines, and strategies to promote sustainable bioenergy practices in the study area.

V. Contribution to ethnobotanical literature: The research contributes to the existing ethnobotanical literature, particularly in the context of bioenergy and Sudanese plant diversity. By documenting the traditional uses of tree species for bioenergy, the study adds valuable data to the scientific knowledge regarding ethnobotany, bioenergy systems, and the cultural significance of plants in the study area. It enriches the global understanding of local plant-based energy practices and facilitates future comparative studies.

1.5 Research outline

This study organized as follows: in chapter one the introduction, objectives, research question and significance of research are highlighted. Chapter two is the literature review chapter which is provides an in-depth understanding of the current information and research gaps linked to the ethnobotanical study on tree species utilized as bioenergy. Chapter three presents the research methodology employed to conduct the ethnobotanical study on tree species used as bioenergy in Sudan. Chapter four offers the various results and discussion. Finally, chapter five reviews the conclusion and recommendations that have been drawn from this study.

CHAPTER 2. LITERATURE OVERVIEW

2.1 Introduction

The literature review section of this research extensively explores the current knowledge and identifies gaps in research for the ethnobotanical study of tree species used for bioenergy purposes. It assists the researcher in determining the relevance of their topic, developing acceptable research goals, designing the research process, and contributing to the field's existing knowledge.

2.2 Bioenergy and its importance

Bioenergy is a renewable energy derived from organic materials that are now or have recently been alive. It is used to produce fuels, electricity, heat, and industrial products (RSPB, 2009). This includes intentionally grown crops such as sugar cane, maize, and palm oil, as well as organic waste, animal products and excrement. The exponential rise in global energy consumption, which has increased 17-fold in the last century, has sparked a growing fascination with bioenergy as a viable substitute (Demirbas, 2006). The biomass industry has experienced considerable expansion, particularly in the biofuels sector, with an annual growth rate of 15%. The increasing acceptance of bioenergy is due to a combination of economic, geopolitical, and environmental reasons.

First and foremost, the rise in oil prices has sparked enthusiasm for alternative energy sources. The correlation between oil prices and interest in biomass is clear to see, as evidenced by the blossoming of bioenergy technology in the 1970s when the cost of oil skyrocketed and its decline in the 1980s when oil prices were low. The scarcity of oil and the exorbitant prices per barrel have sparked a renewed interest in research into the use of bioenergy. Many countries are increasingly turning to bioenergy as a more economical alternative to fossil fuels, with governments, businesses and motorists welcoming this change (Biofuel Crossroads, 2006). The correlation between crude oil prices and the share prices of alternative energy companies is obvious, as they fluctuate in lockstep (Polyak, 2006).

In addition, the growing debate about global warming has raised environmental concerns. The comparatively lower CO_2 emissions of biomass as opposed to fossil fuels reinforce its perceived sustainability. This can be partly attributed to the fact that carbon dioxide has only recently been removed from the atmosphere, whereas the carbon dioxide released from fossil fuels has persisted for thousands of years (Cushman et al., 2007). As a result, the use of bioenergy leads to a significant reduction in carbon dioxide emissions released into the environment. Several countries, including some members of the European Union, are striving to meet the targets set by the Kyoto Protocol by promoting the use of biofuels as a possible substitute for traditional fossil fuels. Considering that biofuels produce lower carbon emissions compared to fossil fuels, their widespread use could lead to a global decrease in carbon production and help these countries meet their carbon reduction targets. Second-generation biomass technology has just emerged as a new category. This involves the production of energy from lignocellulosic plants such as grass, crops, wood, and algae. The energy obtained from these sources can be converted into electricity and fuel through methods such as fermentation and thermochemical conversion. Biomass has three main functions: It can be used as a fuel, it can be used as an energy source, and it can be used to produce industrial heat and related goods (EUROPA, 2007).

2.3 Bioenergy types

Bioenergy comes in a variety of forms and applications. The varieties vary because they employ various types of feedstocks, and the mechanism by which bioenergy is created changes as well.

2.3.1 Biodiesel

Biodiesel, a type of biofuel derived primarily from vegetable oils and sometimes animal fats, is made from a variety of sources, including canola, sunflower seed, soy (widely used in the United States), imported palm oil from Indonesia and Malaysia, jatropha, and spent frying oil. Studies by the U.S. Environmental Protection Agency show that biodiesel has significant environmental benefits compared to petroleum-derived diesel. The integration of advanced biodiesel technology with biodiesel can reduce the release of harmful substances that contribute to the formation of localised smog and ozone depletion.

Biodiesel synthesis is a chemical process, and the resulting product is often blended with conventional diesel. In Germany, a significant proportion of the diesel fuel sold at filling stations contains a maximum of 10% biodiesel. Europe is the world leader in biodiesel production, with Germany, France and Italy accounting for 80% of total production.

Australia, Brazil, India, Malaysia, and the United States are also investing heavily in this particular type of energy. Several governments offer incentives for plants that convert oils and fats into diesel, as well as tax benefits for producers and customers (Agnese, 2006).

2.3.2 Ethanol

In the past, ethanol was traditionally produced by fermenting various plants such as sugar, wheat, rice, potatoes, and corn. Although ethanol is valued in some areas for its economic efficiency compared to gasoline, its main advantage is its lower emission of greenhouse gases. Nevertheless, the benefits of corn-based ethanol, which is primarily used in the United States, have sparked intellectual debate. An inherent limitation of ethanol is its much lower energy density compared to fossil fuels, with some studies suggesting that the energy input exceeds the energy output, making it an unfeasible energy source. Extensive cultivation of agricultural land is important to produce crops used as an alternative to fossil fuels, especially ethanol.

A current trend is the production of second-generation 'cellulosic' ethanol derived from low- cost feedstocks such as plants, wood, and forest residues. In the United States, the use of switchgrass is a prime example of this strategy due to its rapid growth rate and significant biomass production. Switchgrass has several advantages over other crops, such as its ability to withstand adverse soil conditions and extreme temperatures, its higher energy yield, and its self-sufficiency as it does not require fertilisers or herbicides (Biofuel Crossroads, 2006). In addition, second-generation ethanol uses agricultural and forestry waste as feedstock, e.g. straws, leaves, dead wood, small trees, and solid municipal waste such as paper and cardboard (UNCTAD, 2006).

2.3.3 Biomass for heat and electricity

Biomass acts as a substitute power source, known as bioenergy, and is often used in conjunction with or as a substitute for coal in power generation. Feedstocks for power generation include a range of materials, such as agricultural by-products like wheat straw and corn stover, energy crops like hybrid poplars and switchgrass, as well as forestry residues, urban wood waste and mill residues. Farmers also use manure to generate electricity and use sustainable methods to treat biological waste. These feedstocks are classified as second-generation bioenergy, but first-generation crops such as soy and palm oil continue to be used extensively. Anaerobic digestion is the most used technique for converting biomass into electricity, but there are other options. This process converts biomass, such as wood products and animal manure, into methane gas, which can then be used to generate energy with gas turbines in residential and commercial areas. This gas is also used to heat buildings. In addition, the combustion of wood biomass can provide steam to run conventional steam-powered generators comparable to those for fossil fuels. For each type of biomass, certain properties are crucial to ensure optimal energy utilisation (Haq, 2007).

2.4 Biomass characteristics for bioenergy production

The study of biomass involves a comprehensive assessment of the essential elements related to the quality and effectiveness of the feedstock. This includes the analysis of characteristics such as chemical composition, variability, thermochemical properties, hydrolysis, fermentation, and conversion performance, as emphasised by Okafor et al. (2020). The following is an overview of some biomass properties that have a significant impact on biomass quality:

2.4.1 Biomass ash content

Ash from biomass consists of salts that are either chemically bound to the carbon structure, which is called intrinsic ash, or occur in the biomass as mineral soil particles formed during growth or accumulated during harvesting and transportation (Vamvuka et al., 2008). The ash constituents that naturally occur in the fuel are evenly distributed throughout the fuel and have a higher activity level than the enclosed ash constituents. This results in chemical processes taking place during combustion (Dunnu et al., 2010). The mineral content of the ash varies depending on the rotation period of the plant, whether it is long or short or whether it is harvested annually, due to the variable nutrient supply of the soil. Perennial plants, such as trees, primarily accumulate abundant oxides with a low melting point, particularly potassium and phosphorus, while they have much lower concentrations of heavy metals. The main components of the ash composition are silica and calcium oxide, followed by smaller amounts of magnesium, aluminium, potassium, and phosphorus. The combustion of particles leads to simultaneous physical and chemical changes in the inorganic part of the ash. These changes lead to the formation of ash particles through various processes, including segregation, evaporation, precipitation, nucleation, and coalescence. The resulting ash particles can vary considerably in terms of size, shape, and composition. These properties are controlled by several variables, including the morphology and chemical content of the fuel, the temperature at which combustion takes place, and the time the particles spend in the combustion process (Melissari, 2014).

It is important to reduce the amount of biomass ash in the fuel to mitigate the negative impact of gas emissions on the environment and human health. There is also a negative correlation between the ash content and the calorific value of the fuel (Ahmed, 2021). Increased ash content in the fuel leads to the accumulation of fouling or deposits on the surfaces of heat transfer equipment, resulting in equipment deterioration. Corrosion can be caused by the presence of gas phase species, deposits, or a mixture of both. These problems in boilers are significant and can affect the design, life, and operation of combustion equipment. They can also lead to higher operating costs, reduced boiler efficiency, increased carbon dioxide emissions, poorer combustion performance at higher temperatures, increased nitrogen oxide and carbon monoxide levels, reduced heat transfer, corrosion, and erosion. Ash composition, sulphur and chlorine concentrations are the main factors contributing to fouling, deposits, slagging, and corrosion. These elements enhance the movement of various inorganic compounds, especially alkali compounds. To achieve sustainable and consistent progress, it is essential to have a comprehensive understanding of combustion technologies and to adapt them to the different requirements of the fuel. This is particularly important when dealing with industrial waste or energy crops, as these have very different properties to other types of biomass due to their chemical composition. Minerals undergo chemical and physical changes when exposed to high temperatures. These changes include the process of melting, the degradation of volatile chemicals and the breaking apart, fusing, and clumping of mineral particles. It is therefore important to consider the ash concentration in the fuel when planning the plant (Melissari, 2014).

2.4.2 Biomass moisture content

Biomass can be divided into two main categories based on its moisture content: intrinsic moisture, which refers to the moisture naturally present in the material and is not affected by weather conditions, and extrinsic moisture, which is the moisture content affected by weather conditions during the harvesting process (Meincken et al., 2014).

Compared to fossil fuels, biomass generally has a lower energy content and a lower bulk density but has a higher moisture content after harvesting. Therefore, a larger volume of biomass is required to deliver the same amount of energy as fossil fuels. Research has shown that different storage strategies are beneficial to reduce the moisture content. An example of this is research carried out in 2010, which showed a significant reduction in the average moisture content of wood waste from the first to the second year. There was little change in subsequent years, indicating the effectiveness of drying biomass in piles and windrows. However, the results vary depending on the type of wood.

According to the study by Gautam et al. from 2010, softwood species are better suited for large beehives as they allow greater air flow. On the other hand, hardwood species are better suited for smaller hives as their higher branching volume creates more empty spaces in them. The moisture content of the wood refers to the proportion of moisture in the wood compared to its weight when fully dried in the kiln. Wood in its natural form often contains a significant amount of water, often exceeding fifty percent of the weight of a healthy tree. The moisture content of wood plays a crucial role in determining the weight, shrinkage, strength, and other properties of the wood after it has been cut.

Measuring the moisture content is essential due to the hygroscopic nature of wood, which causes it to absorb or release moisture depending on the surrounding air conditions (Ekleman, 2004). The moisture content of wood may naturally vary due to variations in relative humidity and temperature, resulting in dimensional changes such as swelling and shrinking throughout the grain width (Simpson et al., 1993). Wood remains dimensionally stable until its moisture content above the fibre saturation threshold. The fibre saturation point refers to the specific moisture level at which the cell walls are completely saturated, but the cell lumens contain no water. On average, in the United States, this threshold is often estimated to be around 30% for most species. However, it may vary between species and individual pieces of wood owing to intrinsic natural variance.

The fibre saturation point notion emphasizes the differentiation between bound water and free water in the material, which represents the two methods by which water is kept in wood. Bound water is securely retained inside the cell wall due to strong adsorption forces, particularly hydrogen bonds. It undergoes absorption into the cell wall's cellulose, hemicellulose, and lignin components as a result of hydrogen-bonded attraction. The density of wood is closely associated with the size of its pores, which means that it is more difficult to extract bound water from denser species compared to species with lower density and wider pores.

The presence of weak hydrogen bonds in the cell lumina allows for the extraction of free water in its liquid form. Typically, the mechanical characteristics of wood enhance as it undergoes the drying process. The enhancement is especially evident when the wood undergoes drying below the fibre saturation threshold, as it leads to a substantial increase in both strength and elastic qualities. This phenomenon arises due to the departure of water from the cell wall, which enables the convergence of long-chain molecules, leading to a more compact and stronger connection. The process of drying wood for bioenergy production has several advantages. The technique of lowering moisture content prevents fungal activity by creating circumstances that are less favourable for fungi to flourish. Fungi usually need greater moisture levels than the fibre saturation point (FSP) to grow and multiply. Furthermore, the weight of dehydrated logging waste is significantly reduced, resulting in cost savings during transit. Furthermore, the net thermal values exhibit an augmentation when the wood is devoid of moisture, since this factor is intricately linked to the moisture content of the biomass (Normand, 2020).

2.4.3 Biomass calorific value

The calorific value is an essential characteristic of any fuel, indicating the overall energy content of the fuel by measuring its heat availability. The attribute in question is mostly determined by the chemical makeup of the fuel and may be categorized into two separate kinds.

- The higher heating value refers to the total heat energy available in the fuel, including the energy included in the water vapor in the exhaust gases.

- Conversely, the lower heating value does not consider the energy related to the water vapor.

Within the domain of biomass combustors, the widely acknowledged standard is the Higher Heating Value (HHV), while some manufacturers may choose to use the Lower Heating Value (LHV), which might lead to possible misunderstanding. Specific biomass species have different energy densities per unit of mass. Nevertheless, the differences seen across species are often similar in magnitude to the intrinsic variances found within a certain species. The thermal energy content of biomass fuel is susceptible to significant variations due to factors such as climate, soil conditions, and other environmental variables. Therefore, it is more precise to perceive the energy content of biomass fuel as a range rather than a constant value. Figure 1 depicts the standard spectrum of some frequently used fuels. The statistics indicate a clear pattern where wood, which has lower ash content, generally has a somewhat greater heat value than field crops (Ciolkosz, 2010).

2.5 Ethnobotany and its relevance

Across history, people from many cultures have continually relied on plants to fulfil their fundamental requirements, such as food, housing, heat, and medical treatments. As individuals migrated in a nomadic manner, they exchanged their understanding of plants with nearby tribes, whether they were friendly or adversarial, resulting in the steady collection of botanical knowledge. As a result, this extensive knowledge of plants has been transmitted from one generation to another, with the plants themselves frequently spreading consequently. The study of plants and its many uses is a basic human endeavour that has been pursued by cultures for thousands of years, predating the formalization of the word "ethnobotany." Introduced by John William Harshberger (1895), ethnobotany is an interdisciplinary field that examines the interplay between plants and humans, combining the study of people (ethno) with the study of plants (botany). Ethnobotany is a multidisciplinary scientific area that explores the relationships between plants and humans. It falls within the wider topic of ethnobiology, as described by Schultes (1992). The focus of this study is to comprehend the ways in which plants have been or are used, managed, and perceived by human communities. This comprises a diverse range of plant uses, including but not limited to food, cooking, heating, medicine, divination, cosmetics, dyeing, textiles, building, tools, money, clothing, rituals, social activities, and music. The evident importance of the complicated relationship between humans and plants is everlasting. Plants have a vital part in all aspects of our existence, since they control the levels of gases in the atmosphere and are the only organisms capable of turning sunlight into the nourishment that sustains all other living beings. In essence, the existence of plants is vital for life as we understand it. Indigenous tribes possess a wealth of knowledge about medicinal plants and play a crucial role as the main source of information for practical uses. Ethnobotany may be classified into two primary classifications. One fundamental aspect of ethnobotany is the collection and organization of information about plants and animals from indigenous and other sources. This encompasses data on advantageous flora and fauna, knowledge of ecological management techniques, and comprehension of language categorizations. Our objective is to do this work in the field, directly from primary sources, and arrange the findings after species identifications are completed. Essential aspects of quantitative and experimental ethnobotany are the recording of information, the measurement and evaluation of use and management practices, and the conduct of experimental assessments.

Historically, ethnobotanical study mostly concentrated on conducting surveys of plants used by rural communities. Currently, ethnobotanical surveys include practical efforts focused on improving the socioeconomic circumstances of these communities. This method enables individuals to make well-informed choices on their future. The utilization of these novel approaches improves the caliber of research, offers recompense to cultural groups, and tackles environmental issues (Pandey et al., 2017).

2.6 Ethnobotanical research methodologies

Because of the use of quantitative approaches, the scientific rigor of ethnobotanical research has grown considerably during the last two decades. By and large, ethnobotanists have recognized and responded to the need for research based upon the hallmarks of the scientific method, including testable hypotheses, reproducible methods, and statistical measures of variation. Quantifying valid and comparable measures for less tangible qualitative data is a substantial problem within the realm of quantitative analysis. Considerable progress has been achieved in the development and use of Relative Cultural Significance (RCI) indices. These indices entail the establishment of numerical scales or values for each plant taxon, drawing from the disciplines of social sciences and ecology (Phillips, 1996). The incorporation of RCI indices into the field of ethnobotany began in the late 1980s. Boom (1990) conducted significant research where he calculated the proportion of plants used by Panare indigenous informants in a 1-hectare forest patch in Venezuela. This study served as a fundamental foundation for making measurable cross-cultural comparisons of plant knowledge. Recognizing the varying importance of various applications, Prance et al. (1987) proposed weighted indices, allocating a value of 1.0 to significant uses and 0.5 to less important uses. Although this technique sought to include different degrees of significance, it failed to account for differences across informants. A pivotal event in the field of quantitative ethnobotany came when Phillips et al. (1993) published their research on the usage values of RCI. The authors evaluated the variance across informants by treating each instance of use-citation frequency as a statistical "event."

2.7 Tree Species as Bioenergy Sources

Multiple terminology has been used to describe forest systems that primarily, and often alone, produce biomass for energy purposes (Suchomel et al., 2012). These systems have unique geographical and temporal characteristics. The distinguishing characteristics of these systems, as opposed to agricultural crops or other forest systems, are their low risks, strong economic feasibility, flexible harvest schedules, worldwide accessibility, potential for increasing biodiversity (particularly when integrated with agricultural crop portfolios), and the possibility of being used for phytoremediation purposes (Dimitriou et al., 2015). When developing energy plantations, it is crucial to carefully analyse the choice of species, density, rotation, harvest cycles, location, and management strategies.

Choosing the right species is extremely important, giving preference to those that have a high production of biomass when dry, strong ability to sprout, fast growth during their early stages, narrow crowns, or large leaves in the upper part of the tree, biomass with high specific energy and quality, ability to adapt to different environments, and resilience to living and non-living factors (Vávrová et al., 2017). Hybrids are often used to increase output because of their capacity to adapt to climatic circumstances and their resistance to diseases (Ceulemans et al., 1996). Populus spp., Salix spp., and Eucalyptus spp. are the three most often mentioned species for energy plantings, as stated in the literature (Guidi et al., 2013). The primary objective of energy plantations is to attain optimal productivity within a minimal timeframe. Consequently, the density, rotation, and harvest cycles are closely interconnected.

The regulation of density and rotation in a stand is governed by three principles: the ultimate constant yield rule, the establishment of social classes, and the self-thinning law (Sixto et al., 2007). The densities range from 1000 stems per hectare to 310,000 stems per hectare, while the rotation periods range from 1 year to 20 years. There is a clear division between density and rotation, where greater densities are often associated with shorter rotations, while lower densities are associated with longer rotations (Suchomel et al., 2012). The duration of harvest cycles, which may vary from 10 to 30 years, depends on factors such as the death of stumps, the capacity of plants to regrow, and the frequency of cutting.

The choice of site has a direct impact on the ability of tree species or clones to survive, thrive, and provide a harvest. Productivity is increased on high-quality sites with longer growing seasons, and steep slopes should be avoided in situations involving machines. Optimal management of natural vegetation to reduce competition with spontaneous growth is most successful during the first stages of site preparation, but further control measures may be required after harvesting.

Planting procedures provide two primary options: propagation via cuttings or using seedlings. Salix spp. generally use the former option, but Populus spp. or Eucalyptus spp. prefer the latter option (Ceulemans et al., 1996; Suchomel et al., 2012). Management options include either implementing coppicing after one year to stimulate growth or conducting the first harvest at the conclusion of the rotation. The practice of fertilization is a subject of discussion, with differing opinions on its effect on crop productivity. Some say that it improves yield, while others hold a contrary view (Sixto et al., 2007). Pathogen control largely entails the selection of resistant species or clones, the promotion of variety, and, if needed, the use of phytopharmaceuticals. Irrigation plays a vital role in mitigating water scarcity and minimizing the negative impact on plant development.

2.8 South Darfur State: Geographical and Environmental Context

South Darfur State, located in the western portion of Sudan, is acknowledged as one of Sudan's 18 states, covering distinctive physical and environmental characteristics in the Darfur area. Recently, this area has seen a multitude of difficulties, including as violent confrontations, mass migration, and ecological deterioration. South Darfur State spans an area of almost 127,300 square kilometers and is next to North Darfur in the north, East Darfur in the east, and Central Darfur in the northwest. Furthermore, it shares an international border to the west with Chad. Nyala, the state capital, serves as the central location for administrative and commercial activities in the area.

The geographical features of South Darfur State consist of arid plains, rugged plateaus, and elevated mountain ranges. The Jebel Marra mountains, located in the north-western part, stand out as the highest and most notable, reaching an altitude of around 3,000 meters. The mountains in this region have a significant impact on the area's hydrology since they collect rainwater and provide as an essential water supply for nearby communities.

The climate of South Darfur State is mostly arid, with very hot summers and somewhat moderate winters. The region is characterized by a semi-arid to desert environment, with an annual precipitation range of 100 to 400 millimetres. Precipitation, with an unpredictable pattern, is most abundant from June to September. Nevertheless, the state has lately faced the issue of drought, resulting in water scarcity and agricultural difficulties. South Darfur State is greatly concerned about the destruction of the environment, since it is facing significant issues like deforestation, desertification, and soil erosion. The difficulties at hand are influenced by many factors, including population expansion, unsustainable farming methods, and increasing grazing. These factors together contribute to the exhaustion of natural resources. Deforestation has led to the depletion of forested areas and the reduction of important tree species such as Acacia spp., which plays a significant role in Sudan's economy by serving as a valuable export, particularly in the form of gum. The environmental challenges in South Darfur State have extensive consequences for both local inhabitants and the broader ecology. The depletion of vegetation and degradation of soil have led to a decline in agricultural productivity, which poses a significant risk to both food security and livelihoods. Additionally, the population's relocation caused by war has exacerbated the pressure on natural resources, as individuals seek out new territories to inhabit and satisfy their needs.

The Sudanese government and foreign organizations have undertaken initiatives to tackle environmental concerns in South Darfur State in response to these difficulties.

Initiatives such as reforestation, land rehabilitation, and sustainable agriculture have been implemented to mitigate the negative impacts of environmental degradation. Nevertheless, the continuous occurrence of violence and political instability in the area poses substantial challenges to these endeavours. South Darfur State is geographically defined by arid plains, rugged plateaus, and the Jebel Marra mountains. The region is now experiencing persistent environmental challenges, including deforestation, desertification, and soil erosion. These issues pose significant risks to both the local people and the ecological equilibrium. The region's persistent violence and instability hinder growth, despite continued attempts to address these challenges (SECS, 2019; UNEP, 2012).

2.9 Ecological and socioeconomic implications of bioenergy use

Energy is not only a vital national resource, but it also serves as the essential material basis for a nation's social and economic progress. The limited availability of conventional fossil fuels such as coal and oil in recent times, along with increasing environmental apprehensions linked to their utilization, has greatly hindered worldwide advancement. Numerous nations see the advancement of novel energy sources as the principal remedy to tackle the energy predicament and as a vital element of their expansion strategy.

Renewable energy is crucial in the investigation of alternative energy sources (Omer et al., 2008). Out of all these options, bioenergy is often recognized as a renewable energy source (Timmons et al., 2010). The production of bioenergy is seeing a significant expansion in both industrialized and developing nations, as seen by the growing output in countries like the United States and China. The global output of bioenergy had a significant increase, growing almost fivefold from 10,021 thousand tons of oil in 2001 to 58,457 thousand tons of oil in 2010.

The benefits of biofuels, including as their renewable nature, environmental friendliness, and economic effectiveness, are widely acknowledged on a worldwide scale. These benefits are seen as not only tackling the difficulties in fossil energy supply, optimizing the energy composition, and guaranteeing national energy stability, but also reducing greenhouse gas emissions, promoting regional economic development, and increasing farmers' income. Nevertheless, despite the advantages, there are ongoing problems and conflicts related to the expansion of bioenergy (Serra et al., 2013).

2.10 The ecological effects of bioenergy

Essentially, the use of non-renewable fossil energy throughout the energy life cycle, which includes exploration, production, transportation, consumption, pollution treatment and other activities, is a critical element (Hill et al., 2006). The classification of energy renewability can be divided into three different categories: absolute renewability, in which no fossil fuels are used at any stage of the life cycle; partial renewability, in which the consumption of fossil energy is less than the total energy contained in the life cycle; and non-renewability, which indicates that the consumption of fossil energy throughout the life cycle exceeds the energy contained in it (Pradhan et al., 2013).

Some experts believe that biofuels produced through the process of photosynthesis meet the criteria to be classified as renewable energy sources. Creating a well-designed framework for the development of biofuels is considered crucial for achieving sustainable development (Hoeoek et al., 2013). Shrestha and Pradhan (2012) proposed the net energy ratio (NER) as a measure of energy efficiency, which is equivalent to the fossil energy ratio (FER). The NER is determined by the energy life cycle analysis (ELCA). This ratio quantifies the energy output in relation to the energy input and serves as a measure of the sustainability of biofuels. If the fuel-to-energy ratio (FER) is zero, the biofuel cannot produce any energy. If the ARR is greater than zero but less than or equal to one, the biofuel is considered non-renewable. However, if the ARR is greater than one, the biofuel is renewable to a certain extent.

In their study, Kumar et al. (2012) used a life cycle approach to assess the degree of renewability of jatropha biodiesel. They discovered that the net energy ratio (NER) values varied between 1.4 and 8.0 depending on many parameters such as the distribution of energy and emissions as well as the techniques used for irrigation. Rajaeifar et al. (2014) examined the energy life cycle of biodiesel from soybeans in their study and found that the FER (Fuel Energy Ratio) was 1.97. Renó et al. (2011) found that the FER (fermentation efficiency ratio) for methanol synthesis from sugar cane bagasse was 9.4. Pimentel and Patzek (2005) found that an FER (Fuel Energy Ratio) of over one was achieved in the production of ethanol from food and crops in the United States. Mohammad Shirazi et al. (2014) found in their study that the ratio between energy output and input in the production of biodiesel was 1.49. Of this, 77.31% of the energy was renewable, while 22.69% was non-renewable. In their study, Garcia et al. (2011) performed energy balance calculations to determine the ratios in the production of sugarcane ethanol fuel in Mexico, which ranged from 1.1 to 4.8. Timmons et al. (2010) conducted a simulation in New Hampshire and found that the diesel fuel used to produce and transport woody biomass contains less than 2% of the total energy potential of woodchips.

Nevertheless, there is a large body of research that raises scepticism about the renewable properties of biofuels. Yang and Chen (2012) found that the cost of non-renewable energy was 1.7 times higher than the energy produced by corn ethanol. In addition, Chen, and Chen (2011) found that the total energy input of rapeseed oil-based biodiesel exceeded the energy output of biodiesel by a factor of 1.1. Bureau et al. (2010) attributed the contradictory results to two main variables. Resource endowment, climatic conditions, economic variables, and technology can lead to variations in inputs such as labour and raw materials (e.g. nitrogen) in the production of biofuels. In addition, differences in the research methodology of different studies can lead to discrepancies in the final analysis, such as the inclusion of fossil fuel consumption resulting from by-products in the biofuel production life cycle. In some studies, the energy from all fossil fuels burned as by-products was included in the calculation of energy consumption in biofuel production. In other studies, however, this was not considered, resulting in different fuel-to-energy ratios (FER) or net energy estimates for biofuels. Furthermore, the use of different life cycle boundaries for the assessment led to different results, as the study by Heller et al. (2004) shows. Their study on electricity generation from raw willow showed that the FER (fuel to energy ratio) was 55 when only the cultivation and harvesting of the raw material was considered. However, when the processes of cultivation, extraction and transportation of the raw materials are considered, the FER drops to 35.7. The inclusion of cultivation, extraction, transportation, and electricity generation from raw materials in the overall process caused the FER to drop further to 13.3.

2.11 Influence of bioenergy use on local livelihoods and rural communities

Biofuel deployment has both positive and negative impacts on rural income. At a larger level, it has an indirect impact on income via market-based multiplier and equilibrium effects, mostly influenced by government policies, especially in the United States and the European Union. Furthermore, other countries such as China, India, and Brazil have implemented requirements, fiscal benefits, or financial support for the development of biofuels. Simulations indicate that the rising need for bioenergy leads to a net rise in rural income. The increase in earnings in the biofuel industry might raise wages in rural areas, resulting in improved consumption and downstream effects on the market. Nevertheless, when remuneration in the agricultural sector rises, the ability of non-agricultural persons to buy goods and services may decline.

There are several methods of production, including plantations, contract farming, autonomous smallholder farming, and subsistence farming. Cultivating sugarcane and soybeans, often on a big scale with robotic harvesting, may substantially decrease labour expenses. Although automation may enhance wages and working conditions for experienced labourers, it can also diminish job prospects by substituting small-scale farming with large-scale plantations. Unskilled labour on plantations is often temporary, poorly compensated, and characterized by difficult working conditions, which contributes to the ongoing marginalization of workers.

There are specific difficulties in the production of biofuels, especially when sugarcane contract farmers may not get financial benefits due to the company's authority over activities such as ploughing, providing seed cane, and covering transportation costs. Although local biofuel production for local consumption has promise for generating livelihood benefits, there is a scarcity of peer-reviewed research on this production strategy. Jatropha, a feedstock with restricted use for energy production, distinguishes itself from other feedstocks that have broader applications, such as food or other commodities. The plant's performance has been impeded by a deficiency in agronomic knowledge and inadequate profitability (Hunsberger, 2014). The selection of feedstock has a direct influence on the income of producers, considering the production cycle and manpower demands. Choosing slow-growing feedstocks such as jatropha or oil palm may require farmers to delay receiving money until the harvest. This might benefit wealthy farmers who have other sources of income or significant savings (McCarthy, 2010). The size of production has a notable impact on both income and distribution. Smallholders, in comparison to bigger farmers, have greater risks of crop failure or reduced yields owing to their limited upfront investment and management capacities.

In contrast, smallholder contract farming programs may use economies of scale in certain chores while still benefiting from the benefits of family farming. The advantages and how they are divided depend on variables such as the resources of the scheme operator, their capacity to access the market, the ease of entrance for small-scale farmers, how costs are distributed throughout the production cycle, and the presence of other market options (Gibbon et al., 2010). The presence of local product competition may lead to higher pricing for small-scale farmers, but it also presents a potential threat to scheme operators who depend on a steady supply to pay costs and sustain their market position.

The allocation of revenue advantages and losses in bioenergy production is heavily influenced by contractual agreements. Policies and power dynamics have a significant impact on value chains, determining how value is distributed and who is included or excluded. Importers and merchants that are farther along in the supply chain frequently have the power to set the terms for participation and take a large share of the value that is provided (Bolwig et al., 2010). Local nodes may experience uneven distribution of benefits, which might include institutions such as local governments and farmer cooperatives (Rist et al., 2010).

Under such situations, the objective of inclusion is not the aim. When the circumstances for participating in a global value chain are not favourable, it is more desirable to voluntarily withdraw and engage in alternate activities (Clancy, 2010). Although contract farming offers measurable benefits for small-scale farmers, these advantages are often limited to certain situations (Bolwig et al., 2013). To achieve a more balanced outcome, it may be necessary for small-scale farmers to acquire ownership in facilities that process their products farther downstream, or to establish agreements to distribute the additional value generated from these processes (Clancy, 2010).

2.12 Economic aspects of bioenergy production

Renewable energy sources accounted for 11% of worldwide energy consumption in 2007. Biomass was the main factor, accounting for 1,150 million tons of oil equivalent (Mtoe), which represented 79% of the whole renewable energy supply. Regarding global final energy consumption, biomass ranked fourth with a 10% proportion, falling behind non-renewable fossil fuels such as oil (34%), coal (26%), and natural gas (22%). Biomass refers to organic matter, such as plants or animals, that is burned or transformed to provide energy. Wood is the main source of biomass, although energy may also be obtained from agricultural wastes, animal and human waste, charcoal, and similar fuels.

Biomass may be used in either a direct or indirect manner. Direct utilization, sometimes referred to as conventional biomass utilization, is the process of burning biomass for activities such as cooking, space heating, and industrial applications. On the other hand, indirect or modern utilization entails more complex methods such as gasification for the purpose of energy generation. In economically challenged countries, traditional biomass practices are widespread. These techniques are largely used by over 2.4 billion people, who are mostly among the world's poorest. They depend on biomass fuels such as wood, agricultural wastes, and dung for heating and cooking purposes. Developed countries such as the United States and Europe are progressively demonstrating the use of modern or commercial biomass consumption (Blauvelt, 2007).

Renewable energy technologies provide economic benefits for two primary reasons. First and foremost, these technologies need a greater amount of work in comparison to fossil fuels, leading to a higher level of employment for each dollar spent. Furthermore, these technologies use local resources, resulting in cost savings by decreasing the need for fuel imports. According to the Wisconsin Energy Bureau, the economic advantages of renewable energy are optimized when locally accessible resources can replace imported fuels at a fair price and there is a sufficient supply inside the state. Furthermore, renewable energy sources have the capacity to provide three times the number of employment opportunities compared to an equal investment in fossil fuels, as stated by the National Renewable Energy Laboratory in 1997.

The Biomass Energy Resource Centre (BERC), an autonomous non-profit organization supporting communities, educational institutions, governments, businesses, and utilities in the advancement of biomass energy projects, delineates the diverse beneficial effects of biomass energy on local and regional economic growth.

- The local economy is positively impacted by the creation and maintenance of employment via the local production, harvesting, and processing of biomass fuel.
- In contrast to fossil fuel systems that often send money out of the local economy, the expenditure on biomass fuel stays within the local economy. Constructing and upkeeping biomass energy systems have a positive impact on job prospects within the local economy.
- The regional forest products industry achieves growth by discovering inventive methods to utilize forest by-products as fuel, resulting in the establishment of fresh local markets.
- Biomass projects contribute to substantial local, state, and federal tax revenues as a result of the economic activity and employment opportunities they generate. The job possibilities and economic development provided by biomass initiatives lead to the generation of substantial municipal, state, and federal tax revenues.

- Figure 1 depicts the multiplier effect, demonstrating the many economic benefits that result from investments in renewable energy technologies:

- Direct consequences are to the on-site employment and revenue that arise from the original investment, such as personnel engaged in the assembly of wind turbines at a manufacturing facility.

- Indirect impacts refer to the supplementary employment and economic activity that is connected to the provision of products and services related to the main activity. This includes professionals such as bankers who provide loans to plant owners, as well as workers who provide components to turbine assemblers.

- Induced effects pertain to the employment and economic activity that arises from the expenditure of wages received by those directly and indirectly engaged in the industry. This includes the creation of jobs when manufacturing plant workers use their pay to make purchases at nearby establishments such as grocery shops.

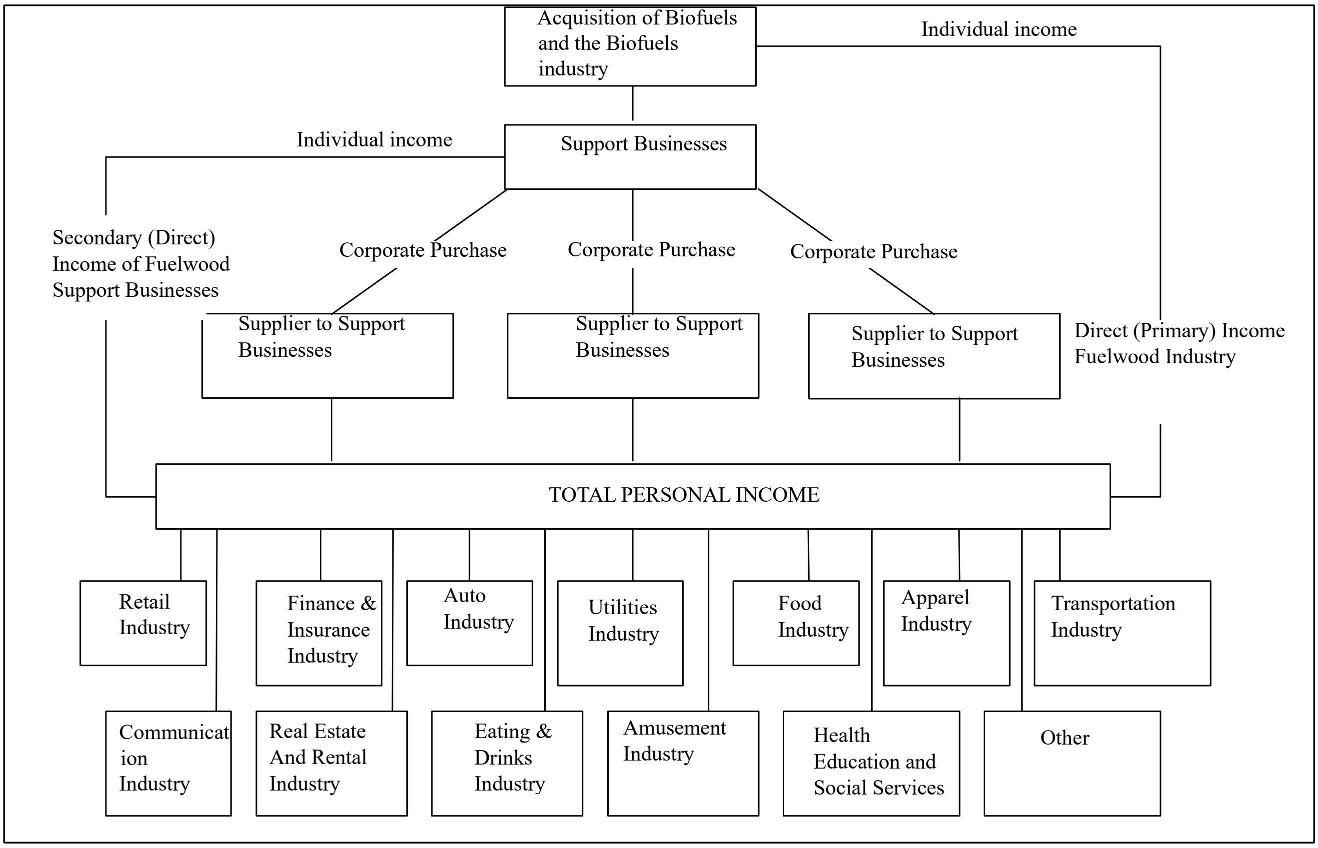

Figure 1. The economic ramifications of the fuel wood business

Source: NREL (1997)

Examining the financial and environmental consequences of using biomass is essential for making informed choices about sustainable development strategies. To tackle significant obstacles, it is necessary to analyse the consequences of heightened biomass use on agricultural markets, pricing mechanisms, land distribution for food cultivation, and overall food security. The economic and environmental advantages of biomass usage differ according on the level of examination. The valuations of benefits and costs depend on elements such as personal viewpoints, community deliberations, national circumstances, and particular industries or businesses. An assessment of the economic benefits at several levels, including individual establishments, communities, and the country, offers a thorough comprehension. This involves evaluating the viability of biomass energy systems in comparison to other energy sources, particularly fossil fuels, or the replacement of traditional crop production with the growth of energy crops at an individual level. At the community level, economic value considers elements such as the creation or loss of jobs, effects on the tax base, and alterations in infrastructure. National-level analysis encompasses the interplay and impacts of bioenergy production on farms, facilities, and users. It examines the overall economic value added, trade balance, job creation or loss, government expenditures, national security implications, and the economic cost and efficacy of environmental regulation. The diverse evaluations add to a worldwide understanding of the consequences of biomass consumption (Congress of the United States, 2007).

2.13 Challenges and constraints in bioenergy utilization

The use of wood to make energy has grown a lot around the world. This is mostly because of laws in the US and the EU that encourage using green energy (US Congress, 2007). By reducing the country's reliance on fossil fuels, these rules are meant to improve energy security and lessen the damage that transportation does to the environment. Bioenergy is the use of different types of plant products and processing processes to make heat, electricity, or fuels. In comparison to traditional fossil fuels, Creutzig et al. (2015) indicate that this method has the potential to greatly lower greenhouse gas emissions.

Still, the growing number of biofuel plant farms around the world makes people worry about their long-term viability. People are worried about the problems that could happen because of direct (DLUC) and indirect (ILUC) changes in land use that could have an impact on food production. Concerns have also been raised about the high levels of nitrous oxide (N2O) that are released when fertilizer is used, and the soil is disturbed. Concerns have also been raised about the impact on land and water supplies, especially the loss of organic carbon stores in the soil. These issues could lead to bad outcomes (DeCicco, 2013).

A lot of people have strong opinions about the environmental effects and advantages of bioenergy, especially first-generation biofuels made from foodstuffs like grains and oilseeds. Studies show that compared to fossil fuels, there is a big drop of 86% to 93% in greenhouse gas emissions over the whole life of the plant (Whitaker et al. 10). However, Crutzen et al. (2008) say that the N_2O emissions from the growth of biofuel feedstocks are not considered enough. Moving food production to places that store a lot of carbon or are important for protection also comes with a risk. This is called indirect land use change (ILUC). Fargione et al. (2008) say that this could cause a carbon debt that won't be paid off for many decades. Davis et al. (2013) and Mello et al. (2014) say that these problems could be solved by using better management techniques or cutting down on the time it takes to get back the money spent. Legal steps have been taken to cut down on indirect land use change (ILUC), but there are still big concerns about what it means (Del Grosso et al., 2014).

According to Creutzig et al. (2015), bioenergy made from dedicated perennial crops should have lower greenhouse gas (GHG) emissions over the course of its full life cycle and have major environmental benefits compared to bioenergy made from yearly crops. Less nitrogen is needed by perennial plants like miscanthus, SRC willow, and poplar, which lowers N_2O releases and improves water quality. They are also able to absorb and hold on to carbon in the soil by reducing tilling and putting more resources into below-ground biomass. This method has been shown to be cost-effective when used on poor or damaged soils, getting around problems with other farming methods and the effects of indirect land use change (ILUC) (Carvalho et al., 2017). Because it produces a lot of sugar and can be used to make energy, sugarcane is a long-lasting plant that helps reduce greenhouse gas (GHG) pollution in a big way. This effect is especially important in Brazil, where modern machine gathering methods have made the earth much better at storing carbon (Silva-Olaya et al., 2017). But having permanent crops can change the way ecosystems store carbon through changes in land use in different ways, based on the soil type and the weather conditions at the time (Field et al., 2016). It's hard to get a good idea of the effects of different land uses and the special features of land that has been turned into biofuel crops. This makes the total greenhouse gas (GHG) balance of bioenergy very unclear (Davis et al., 2013).

2.14 Constraints faced in sustainable bioenergy production and utilization

In view of the growing global demand for biofuels, scientists are increasingly focusing on the intersection of sustainable development and bioenergy. The IPCC Working Group III has published a supplement to the Fifth Assessment Report (WGIII AR5). This study examines the link between unique situations, the use of biofuels to prevent climate change and the long-term impacts on development. The use of bioenergy can have different impacts on long-term growth depending on the system, development context and scale of activities (Smith et al., 2014).

Several case studies show that increased cultivation of crops commonly used for biofuels can have a variety of impacts on local income, food security, land tenure and health. The benefits of biofuel production can be unevenly distributed (Persson, 2014). Sustainability concerns have been investigated using model-based research to identify possible links between biofuel, food prices, wildlife, and water use (Popp et al., 2011). However, further research is needed to determine how bioenergy affects human survival and how policies could improve or mitigate certain impacts (Smith et al., 2014). Previous research has also shown the importance of better understanding the links between biofuel production, employment, and equity (Hunsberger et al., 2014). Given the compelling need to address climate change (IPCC, 2014), persistent economic and social inequalities and increasing land competition (Haberl, 2015), policy makers should consider scientific evidence on the impact of biofuels on sustainable development.

2.15 The international energy policy context

Energy policy is now one of the world's most controversial issues. The conversation in industrialized countries, particularly in the EU and the United States, typically revolves around topics such as guaranteeing energy security and self-sufficiency, decreasing dependency on foreign fossil fuels, and dealing with the consequences of rising oil and natural gas prices. Furthermore, bioenergy policy considers the potential to boost the agricultural sector. Furthermore, bioenergy policy is consistent with the environmental protection objectives specified in several international accords, notably those aimed at reducing greenhouse gas emissions. These reasons are essentially driving the increased use of biofuels and other renewable energy obtained from biomass.

Over the last several decades, governments have developed and executed national bioenergy plans in a broader political, economic, and environmental framework. The motivation to encourage the production and use of biofuels in the United States began in the early 1980s, owing in part to the need to reinvigorate agriculture. These legislative actions were backed by the Clean Air Act and the Reformulated Gasoline Program, which were enacted in the early 1990s. The present US policy, stated in the Energy Policy Act of 2005, includes state and federal tax incentives for fuel ethanol and biodiesel, as well as a federal tax credit for gasoline ethanol that is valid until 2010. The Federal Bioenergy Program offers loans, credit guarantees, and incentives to farmers and biofuel producers. Notably, state governments have outpaced the federal government in their support for biofuels. Fuel ethanol producers may get a variety of subsidies, including direct payments, grants, low-interest loans for ethanol production facilities, tax credits, extra fuel tax exemptions, and other kinds of aid. The European Union's Biofuels Strategy is motivated by the need to diversify fuel sources, address climate change impacts, and explore new trade and business prospects for European industry and farmers. The European Commission has played a major role via directives, recommendations, and research. The Biofuels Use Directive (2003/30/EC) required 5.75% ethanol and biodiesel blends in gasoline and diesel, respectively. The guideline is being revised owing to its conflict with the 2003 fuel quality directive, which restricted biodiesel blends to 5%. However, since blending is voluntary, member nations may impose stricter requirements. A variety of variables, including the political context, impact national bioenergy policy frameworks. Brazil's 1975 decision to start Proalcool, a renewable energy initiative, was driven by lower energy bills, more hard currency revenue, and worries about energy independence. Despite being under military rule and isolated, Brazil has become a major producer and exporter of ethanol. A biodiesel campaign in 2002 resulted in the passage of Law No. 11097 in December 2004, which allows for a 2% biodiesel mix. Brazil's current biofuels plan includes governmental involvement in three key areas.

- Regulations require petroleum firms to include 20-25% ethanol into conventional gasoline when combining ethanol and petrol.

- Tax reductions for blended fuels are minimal, accounting for around half of the tax reduction given to pure gasoline.

- Ethanol-powered automobiles pay lower motor vehicle taxes than their gasoline-powered equivalents.

Recent governmental measures in some emerging nations, like Argentina and Paraguay, seem to be primarily motivated by the growing economic relevance of biofuel crops. This is combined with the possibility of considerable export prospects and revenue from biofuel production. Regional pledges to improve biofuel production and consumption have influenced national policy frameworks. In Central America, the Action Plan for the Introduction of Ethanol, for example, requires governments to adopt a variety of steps, including the establishment of an adequate legal framework. Furthermore, the experiences of affluent countries have encouraged similar initiatives in less developed ones. For example, in March 2007, Brazil and the United States signed an agreement to promote and transfer biofuel-related technologies to other Central American and Caribbean nations. Furthermore, private efforts may compel governments to regulate bioenergy activities. An attractive economic environment is critical for encouraging investment in the biofuel business. Concurrently, a regulatory framework is required to set conditions for effective production and usage, protect public interests, and avoid natural resource overexploitation (Jull et al. 2007).

2.16 Socio-cultural factors influencing bioenergy practices

Internationally, there is an increasing need for sustainable energy alternatives. It has been proposed that renewable energy has the potential to provide local environmental and health advantages, as well as increase access to energy for cooking and lighting and provide additional work possibilities. Nonetheless, qualitative research done by Energy for Impact in 2017 found that socio-cultural factors and family structures might impact decisions regarding the best cooking fuel. Socio-cultural traditions, particularly in Africa, have a significant impact on the energy sources utilized by families. This impact is anticipated to be more evident in resource-constrained places where African cultural standards are widely observed (Beck et al., 2016).

2.17 Social cultural determinants

Socio-cultural factors significantly influence people's lives and reflect their living conditions, which are strongly influenced by traditional customs and traditions. Several studies emphasize the influence of cultural attitudes on the adoption of sustainable energy technologies. In a comprehensive study, Urmee (2016) analysed renewable energy projects worldwide and found that the main reason for their failure is the lack of consideration of local culture and socio-economic conditions in the target regions. Culture has a significant influence on cooking methods, preferences, and the acceptance of improved cooking stoves (ICS). The association with the culinary culture of a community positively promotes the use of ICS. Acceptance of ICS is strongly influenced by cooking techniques and food preferences associated with the local culture. Research suggests that people's preference for the distinct flavour of meals cooked on conventional stoves may hinder the acceptance of LPG stoves. This underlines the fact that many traditional recipes cannot be cooked well on LPG.

Social and cultural elements such as religion, customs and traditions, gender, family dynamics, physical health, education level, economic position, marital status, environment and political systems all play a role in shaping these impacts (Eseonu et al., 2014). Cultural norms and traditions provide behavioural protocols and criteria that groups must adhere to. These socio-cultural norms may dictate the location of culinary activities, e.g. in designated areas such as night shelters or kitchen shelters during the day or outdoors when the sun is strong. Therefore, socio-cultural factors have a significant impact on the acceptance of sustainable energy in refugee camps. The refugee families in Kakuma had several thoughts, questions, and doubts about the feasibility of using solar stoves to prepare meals for their families. Social norms, security considerations, education levels, family size and community involvement were cited as major barriers to the adoption of renewable energy technologies. The use of renewable energy in sub-Saharan Africa is increasingly being driven by the recognition of its socio-cultural benefits (Caird et al., 2008).

2.18 Barriers and gaps

Beck et al. (2010) investigated the socio-cultural difficulties present in communities that may impede the execution of renewable energy initiatives, with a particular focus on financial limitations and lack of information as the main hindrances. Owen (2002) discovered that the choice of stove has an impact on the taste of food, however the precise effect is still uncertain. The primary obstacle to embracing renewable technology is the financial aspect, along with practical installation challenges and a lack of understanding. The impact of decreased prices and better knowledge on adoption rates and carbon emissions is questionable, since it may be influenced by the 'Rebound' effect (Caird et al., 2008). Lay et al. (2012) observed that the adoption of sustainable energy technology is influenced by income and education. However, they only focused on social determinants as variables affecting adoption. Energy projects are often seen as gender-neutral, disregarding disparities in energy use patterns between males and females, which jeopardizes customer confidence in renewable energy. Although women play a crucial role as main administrators of home energy, they are often marginalized in energy debates, which limits their participation in the energy sector (UNHCR, 2017). Gender-neutral energy project planning continues to exist despite the significant involvement of women (Glemarec et al., 2016). Mamuye et al. (2018) conducted a study in Ethiopia that examined the influence of gender on the adoption of improved cooking stoves, thereby narrowing the emphasis of previous research on sustainable energy, which mostly focuses on humanitarian groups. Studies conducted in Pakistan and Mexico, as well as Lahn et al.'s (2016) research on the aesthetics of solar power, differ from the specific context of the Kakuma refugee camp in Kenya. These studies focus on a variety of environments and demographics.

2.19 Potential for Sustainable Bioenergy Development

Access to modern, reliable, and long-term energy is critical for attaining food security, agricultural expansion, and poverty reduction. Furthermore, contemporary, inexpensive, and dependable energy is critical for sustaining economic growth, which in turn drives development, poverty reduction, and food security. There are various ways in which a country's food security is harmed by a lack of access to energy. Inadequate availability to cooking fuel may have a detrimental impact on cooking practices by driving individuals to miss meals, switch to less nutritious items that need less cooking time, or undercook food to conserve fuel. Furthermore, irresponsible usage of wood fuel may lead to deforestation and have a detrimental impact on the income of rural people who rely on forest products for a living. Access to modern energy, on the other hand, may act as a vehicle for attaining food security and decreasing poverty by encouraging the formation of rural businesses and productive uses of energy. Similarly, bioenergy may assist farmers in raising agricultural productivity and broadening possible markets for by-products such as crop leftovers. Alternative sustainable energy sources may be employed to expand energy availability while also making energy consumption more sustainable. Bioenergy is one of the renewable energy kinds that may be used as an alternative energy source; it is produced from a variety of biomass sources such as agricultural leftovers, animal residues, and sustainably managed forest resources and residues. A critical component of Bioenergy and Food Security (BEFS) assessment is determining the quantity of biomass that can be obtained sustainably and used to promote development and poverty reduction. In practice, when bioenergy is handled responsibly, it may bring a variety of advantages, including energy, employment, and rural development (FAO, 2020).

2.20 Strategies for promoting sustainable bioenergy practices

Modern bioenergy production has the capacity to either favourably or adversely influence the environment and socioeconomic variables, which in turn may affect the major dimensions of food security, including availability, access, usage, and stability. To guarantee the long-term viability of modern bioenergy development and its compatibility with objectives related to food security, a range of optimal methods may be used throughout the whole bioenergy supply chain. The BEFSCI project has developed a set of ecologically sustainable practices for bioenergy feedstock producers, based on the FAO's work on agriculture and forestry practices. The objective of these methods is to reduce the negative impact on the environment and guarantee that bioenergy plays a role in mitigating climate change, while simultaneously promoting food security.

BEFSCI has identified many socioeconomic approaches to mitigate risks and maximize potential for food security in relation to bioenergy initiatives, in addition to environmental concerns. Nevertheless, the incorporation of these methods may encounter obstacles, including both financial and non-financial aspects. In the absence of suitable legal mechanisms and motivations, the expenses associated with executing these strategies might be excessively burdensome for manufacturers.

BEFSCI has delineated a collection of policy measures to encourage the use of favourable environmental and socioeconomic practices in the production of bioenergy feedstock. These strategies may be used to promote beneficial behaviours and discourage unfavourable ones actively or indirectly. The detected instruments are classified into four primary categories.

- Mandatory requirements emphasize sustainability.
- Certification procedures adhere to national criteria.
- Provision of incentives to solicit financial support.
- Enhancing capacity is given priority.

The efficacy and productivity of these instruments in different nations will be contingent upon many aspects, such as the administrative and enforcement capacity of the individual governments (Rossi et al., 2012).

2.21 Role of local communities and stakeholders in bioenergy management

The bioenergy industry encompasses a wide range of interests and is typically under the jurisdiction of many Ministries. Hence, the development of bioenergy policy and strategy should begin at the ministerial level, promoting cooperation across different policy areas through a multi-ministerial task force or a comparable framework that enables coordination among energy, agriculture, transportation, economics, the environment, and other sectors. Furthermore, it is important for stakeholders to use a comprehensive strategy that involves several stakeholders and sectors. This involves bringing together all relevant parties to discuss the advantages and disadvantages of bioenergy policy recommendations. Every sector or stakeholder provides a distinct viewpoint, which represents the wider concerns of a nation. Academics provide scientific research and information, the commercial sector offers market insights, environmental NGOs prioritize sustainability, community leaders strive to maximize advantages for the less affluent, and interest groups such as women and youth campaign for their people. An ideal result may be achieved by developing a balanced strategy that carefully considers all these interests within the context of national government programs and imperatives. Forming a Task Team or Steering Committee to supervise the policy-making process guarantees the involvement of all relevant parties. The composition of this group would include of individuals from civil society, pertinent government officials, representatives from non-governmental organizations, labour, the business sector, and diverse interest groups, all making equal contributions to the decision-making processes. The Task Team's responsibilities may go beyond the policy phase to include implementation, monitoring, and evaluation, particularly for large-scale projects with substantial implications. In the second stage, a Stakeholder Forum is established, which usually include a wide range of members from the community, community-based non-governmental organizations, the business sector, and other relevant parties who have a vested interest in policy formulation.

The Stakeholder Forum should adopt a more inclusive approach by considering viewpoints that go beyond those of the Task Team. There is no need to restrict the number of the membership, and it is possible to create many chambers or sub-committees to handle needs. It is essential to engage these stakeholders at every level of the policy formation process, starting with the feasibility stage (UNEP, 2005).

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the research technique used to carry out the ethnobotanical study on tree species used as bioenergy sources in Sudan. The chapter provides an overview of the study design, data collecting methods, sampling strategy, data processing methodologies, and ethical issues. This research attempted to systematically explore the traditional knowledge and practices associated with bioenergy tree species in the study region. The goal was to contribute to the understanding of ethnobotanical features of sustainable energy sources.

3.2 Research Design

The study used a research design that included both qualitative and quantitative methodologies. The study used qualitative approaches to get a comprehensive comprehension of the local populations' knowledge, beliefs, and behaviours about tree species utilized for bioenergy. Data on the frequency and distribution of certain tree species and their use patterns were gathered using quantitative approaches. The objective of this study was to get a thorough understanding of the ethnobotanical characteristics of bioenergy tree species in Sudan using a mixed-methods approach.

3.3 Study Area

The research was carried out in Sudan, a country recognized for its abundant biodiversity and varied cultural traditions. The research region was chosen according to UNEP (2008) publications that provided data on biomass fuel usage in Sudan. We chose South Darfur State, which UNEP (2008) has identified as having the highest levels of wood fuel usage and population in Sudan.

3.4 Geographical location of study area

South Darfur State is located in the western region of Sudan, with latitudes ranging from 8°30′ to 13°′N and longitudes ranging from 23°15′ to 28°E. Sudan's 18 states include this one (Figure 2). South Darfur State is situated inside the expansive Darfur region, renowned for its vast plains, elevated terrains, and arid deserts. The state has boundaries with many other Sudanese states as well as other countries. It is next to Central Darfur State to the north, West Kordofan State to the northeast, South Kordofan State to the east, and South

Sudan to the south. South Darfur State has a western border with the neighbouring country of Chad (Abaker et al., 2017).

Figure 2. Study area location in Sudan

3.5 Sampling Technique

A Field survey was conducted in September 2021 to collect primary data from Kalma IDP Camp, Nyala District, South Darfur State, Sudan. Key informants, including experts from the Forest National Corporation (FNC) and individuals who have first-hand information, such as firewood dealers, were interviewed to collect information about the appropriate bioenergy species. A stratified random sampling technique was employed to collect information from three respondent strata; households, brick kiln owners and bakers (Figure 3) with sample ratios of 3:1:1, respectively.

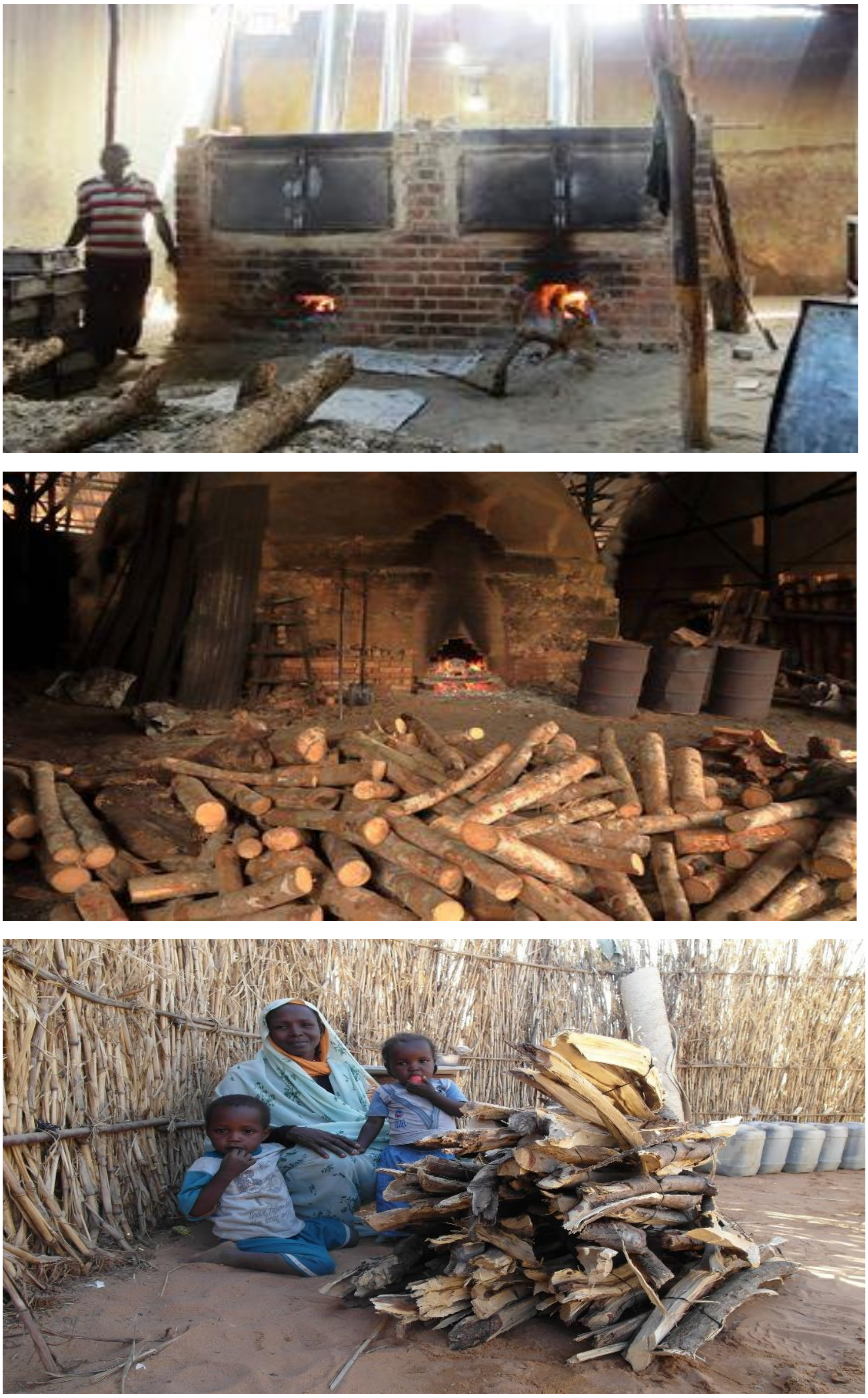

Figure 3. Pictures of traditional bakery, brick kiln and households collecting firewood

3.6 Data Collection Techniques

A mix of techniques using both primary and secondary data gathering methods was adopted to get the necessary data.

3.6.1 Primary Data Collection

The primary data collection involved direct interaction with local communities. The following techniques were utilized:

a) Structured Questionnaire: About 92 questionnaires have been developed to address many topics including key energy species, energy preferences, characteristics, methods of biomass fuel collection, availability of biomass fuel, and consumption categories. A total of ninety-two respondents, including individuals of all ages and genders (both men and females), were questioned. The daily biomass fuel consumption in cubic meters were registered. In addition, group discussions were conducted with the local leaders to supplement and validate the data obtained from the consumer survey.

b) Participatory Observation: I actively participated in the daily activities of the communities, including gathering firewood, cooking, and other activities related to bioenergy utilization. This approach facilitated a deeper understanding of the local context and allowed for the observation of tree species selection, collection, and utilization practices.

c) Focus group discussions: Focus group discussions were conducted with groups of community members to gather collective opinions, traditional practices, and beliefs regarding tree species used as bioenergy. These discussions provided an opportunity for group interactions, knowledge sharing, and the identification of consensus or variations in perceptions (Nyumba et al., 2018).

3.6.2 Secondary Data Collection

Secondary data sources were utilized to complement the primary data. These included relevant literature, ethnobotanical studies, reports, and other scholarly publications related to tree species and bioenergy in Sudan. Such sources were consulted to provide a broader understanding of the historical, ecological, and socio-economic aspects of bioenergy tree species in Sudan.

3.7 Data analysis

The questionnaire data has been transformed into codes. The Statistical Package for Social Sciences (version 26) and Excel Sheel software's were used in data analysis (Ahmed et al., 2023). The qualitative information obtained from the respondents was analysed using frequency distribution and percentage as a tool for interpretation. The use value was computed to determine the tree species most often utilized for energy. It was calculated by the following equation 1:

$$\mathrm{UV} = \frac{\sum \mathrm{Ui}}{\mathrm{n}} \qquad (1)$$

Where UV is the aggregate value of energy trees species, U represents the number of usage reports mentioned by each respondent for a certain species, and n represents the total number of respondents surveyed for a particular species. The fidelity level (FL) was calculated to obtain the relative significance of energy tree species for each consumer group within the research region. Formula 2 was employed in the calculation:

$$FL = \frac{\mathrm{NP}}{\mathrm{n}} \qquad (2)$$

Where NP represents the count of use reports cited for a certain species and usage, whereas N is the overall count of use reports referred for any energy species. The factor informant consensus (FIC) was also computed to determine the tree species that are often used for energy purposes. Equation 3 can be used to compute the FIC:

$$FIC = \frac{\mathrm{nur-nt}}{\mathrm{nur-1}} \qquad (3)$$

Where FIC represents the informant consensus factor, nur represents the number of usage citations in each category, and nt represents the number of species utilized (Khan et al., 2014).

Multiple linear regressions were used to assess the impact of the sociodemographic factors on the biomass fuel consumptions in the study area. The multiple regressions were mathematically expressed according to the following equation 4:

$$R_i = a_0 + a_1 A_i + a_2 C_i + a_3 E_i + a_4 F_i + \varepsilon_i \quad (4)$$

Where R was the daily biomass fuel consumption during the survey period in 2021, i represented the dependent and independent variables. a1-4 represented the coefficient of the variables; α0 represented the intercept term, and ε was an error term. A, C, E and F represented age, gender, level of education and family size, of biomass fuel consumers, respectively (Ahmed et al., 2020).

3.8 Ethical Considerations

Throughout the research process, ethical considerations were prioritized. Informed consent was obtained from all participants before their involvement in interviews. Participants' anonymity and confidentiality were ensured by assigning pseudonyms and using strict data protection measures. The research was conducted with the utmost respect for cultural norms, traditions, and local customs.

3.9 Limitations

It is important to acknowledge the limitations of the research methodology. The study's scope was limited to specific regions in Sudan, which may not fully represent the diversity of bioenergy tree species utilization in the entire country. Furthermore, the reliance on self-reported knowledge and perceptions may introduce biases or variations in responses. However, efforts were made to mitigate these limitations through rigorous data collection and analysis techniques.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the findings of the ethnobotanical study conducted on tree species used as bioenergy sources in the study area. The study aimed to identify and document the tree species utilized by local communities for bioenergy purpose and to understand their traditional knowledge and practices associated with bioenergy use. This chapter presents the findings of the study, including the identified tree species, their utilization patterns, and the potential for sustainable bioenergy production.

4.2 Sociodemographic characteristics of the study participants

This section presents the sociodemographic characteristics of the study participants who provided valuable information on the ethnobotanical use of tree species as bioenergy in the study area. The data collected from 92 individuals, comprising both males and females with varying age ranges, offers insights into the diverse perspectives and practices surrounding the use of tree species for bioenergy in the region.

4.2.1 Gender distribution

The study observed a relatively balanced gender distribution among the participants, with 53 % females and 47% males (Figure 4). This indicates the active involvement and contribution of both genders in the study, highlighting the significance of gender inclusivity when examining ethnobotanical practices related to bioenergy in the study area.

4.2.2 Gender roles and perspectives

The balanced gender distribution in the study enables us to explore the role of gender in the ethnobotanical use of tree species for bioenergy. Understanding gender-specific knowledge, practices, and preferences is vital to promoting gender equality and ensuring that sustainable bioenergy initiatives are inclusive and beneficial to all. Further analysis of gender-related factors, such as access to resources, decision-making power, and participation in energy-related activities, can shed light on the gender dynamics within the bioenergy sector.

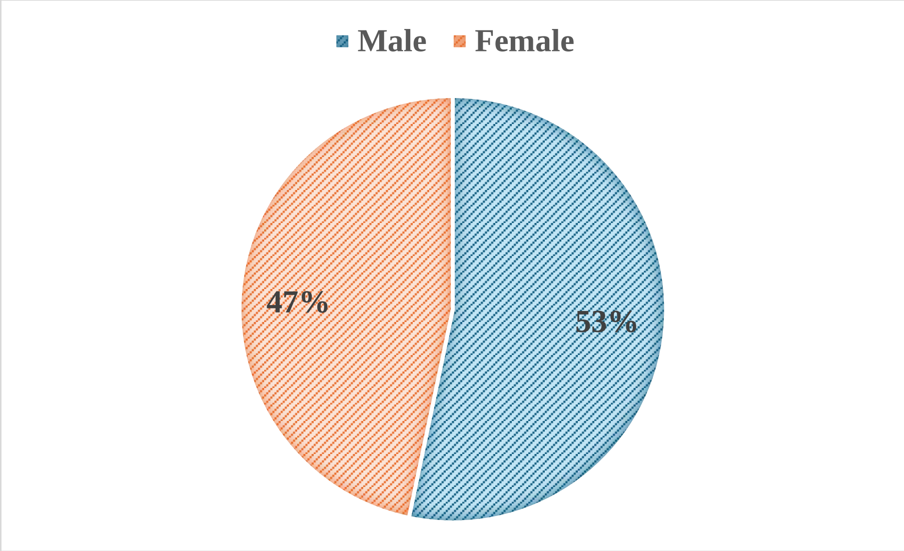

Figure 4. Distribution of respondent's gender

4.2.3 Age range and average age

The participants' age range varied from 19 to 60 years old (Figure 5), providing a broad representation of different age groups within the study. The average age of 34 suggests that the sample population consisted predominantly of individuals in their early to mid-adulthood. This age group is often associated with active engagement in various socio-economic activities, making their perspectives and practices particularly relevant in understanding the ethnobotanical use of tree species as bioenergy.

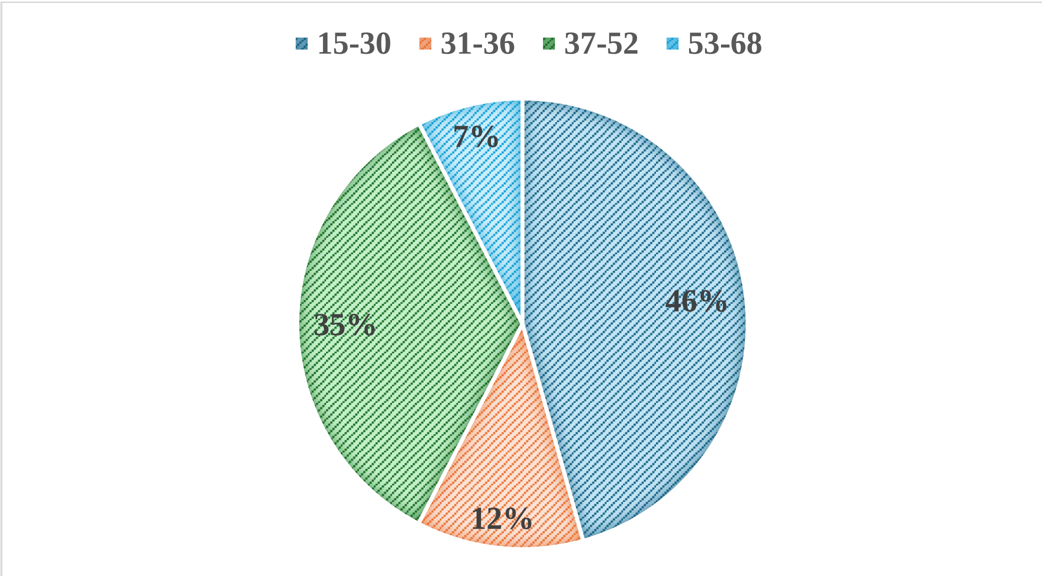

Figure 5. Age of biomass fuel consumer

4.2.4 Age and traditional knowledge

The age range of the participants reflects the intergenerational transfer of knowledge related to the ethnobotanical use of tree species as bioenergy. Older participants may possess traditional knowledge and practices that have been passed down through generations, while younger participants may offer insights into contemporary perspectives and adaptations. Recognizing the contributions and interactions between different age groups is crucial for the sustainable management and conservation of bioenergy resources in the study area.

4.2.5 Significance of sociodemographic characteristics

The sociodemographic characteristics of the study participants play a crucial role in understanding the dynamics of ethnobotanical practices in the context of bioenergy. Gender and age can influence knowledge, preferences, and access to resources, which, in turn, shape the utilization of tree species for bioenergy purposes. Therefore, analysing the sociodemographic factors helps contextualize the findings and allows for a more comprehensive understanding of the topic.

4.3 Education level

The results of the ethnobotanical study revealed interesting patterns in the education levels of the participants. The majority of the participants had an education level that ranged from informal study (Khalwa) to secondary school, with lower percentages observed for primary and university education levels. Specifically, the findings indicated that 33.7% of participants had undergone informal studies, 34.8% had completed secondary school, and 21.7% had attained primary education. Notably, the proportion of participants with a university-level education did not exceed 9.8% (Figure 6).

The distribution of education levels among participants in the ethnobotanical use of tree species as bioenergy has several implications. Firstly, it highlights the importance of recognizing and valuing traditional knowledge systems, which have been instrumental in sustaining bioenergy practices for generations. These traditional knowledge systems serve as invaluable repositories of information and practices that can contribute to sustainable bioenergy production. Secondly, the findings suggest that while formal education can provide a scientific understanding of bioenergy practices, it should be complemented with an appreciation for traditional knowledge. Integrating traditional knowledge into formal education curricula can foster a more holistic approach to bioenergy research and development. Lastly, the limited representation of individuals with university-level education indicates a potential gap between academia and traditional knowledge holders in the field of bioenergy. Bridging this gap through collaborative research, knowledge sharing, and capacity building can help create a more inclusive and comprehensive understanding of the ethnobotanical use of tree species as bioenergy.

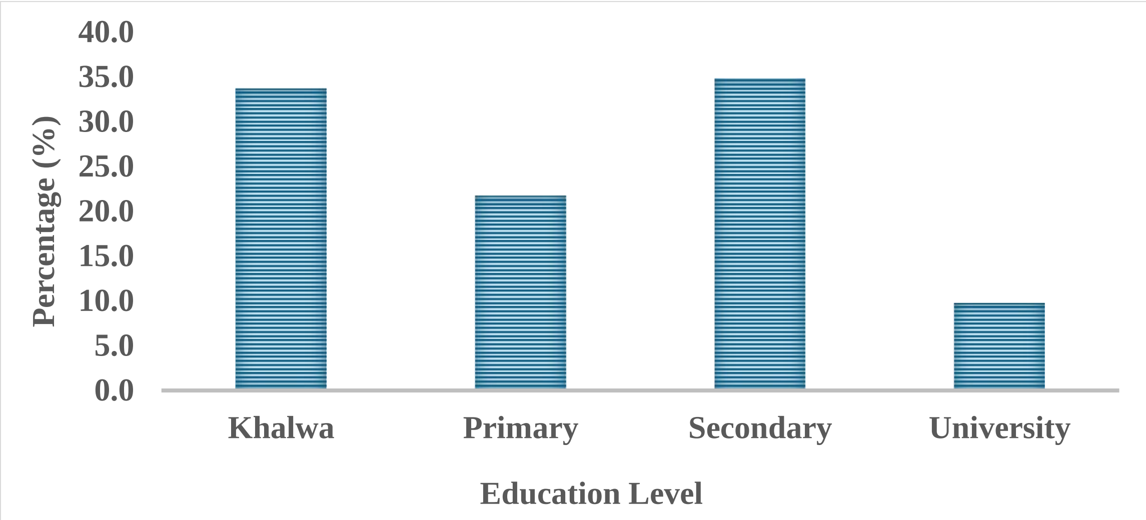

Figure 6. Distribution of biomass fuel consumers according to their level of education

4.4 Available energy sources in the study area

The results revealed that most respondents, approximately 96%, rely on biomass fuel for their energy needs. In contrast, only a small percentage, around 4%, reported using LPG (liquefied petroleum gas) (Figure 7). The survey's results indicate a prevalent reliance on biomass fuel among respondents in the study area. Biomass fuels are derived from organic materials such as wood and crop residues. The widespread usage of biomass fuels can be attributed to various factors, including their availability, affordability, and traditional practices deeply rooted in the culture and lifestyle of Sudanese communities. Additionally, the limited availability and distribution of LPG in certain regions contribute to the prominence of biomass fuel as the primary energy source. The UNEP report from 2008 supports the survey findings, emphasizing the significance of biomass fuel in rural areas and towns in Sudan. These regions often have limited access to modern energy sources like LPG due to inadequate infrastructure and distribution networks. Consequently, the population in these areas heavily relies on biomass fuels to meet their daily energy needs. The use of biomass fuels in such regions have become deeply ingrained in the socio-economic fabric and cultural practices of the communities.

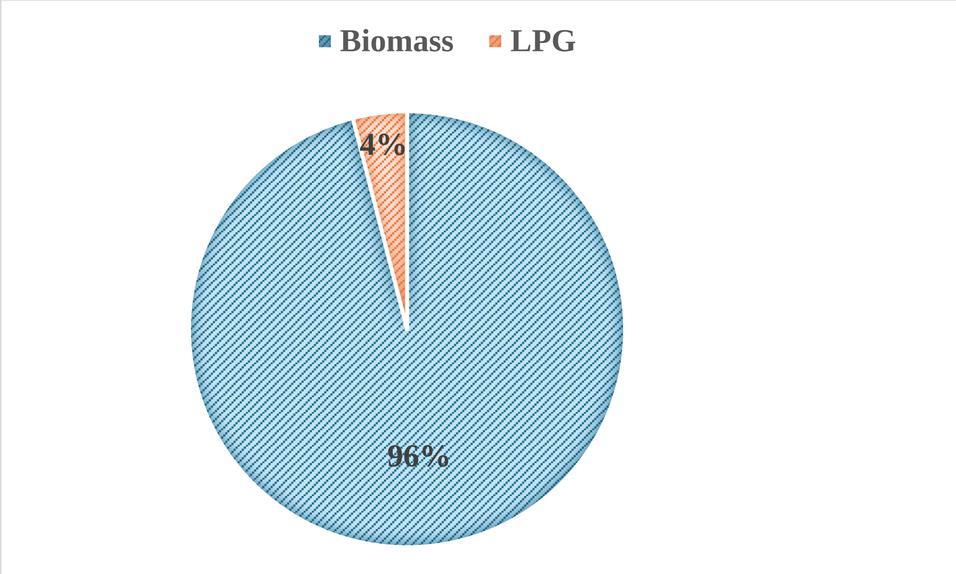

Figure 7. Available energy sources in the study area

4.5 Collection of biomass fuel

The survey findings indicate that the majority of individuals engaged in collecting biomass fuel are males, comprising approximately 50% of the respondents. Females make up a significant portion as well, accounting for around 44.6% of the participants. Interestingly, children constitute only a small percentage, amounting to merely 5.4% of the respondents (Figure 8).

The higher representation of males in biomass fuel collection may be influenced by various socio-cultural and economic factors. In certain regions, traditional gender roles and responsibilities may assign men tasks related to energy provision, such as collecting firewood or other biomass resources. Additionally, economic factors might play a role, as men may be more likely to engage in activities that generate income, such as selling or trading biomass fuel. The significant presence of females in biomass fuel collection is indicative of their active involvement in meeting household energy needs. It highlights their crucial role in the energy sector, as they contribute to the sustainable utilization of bioenergy resources. The participation of women in biomass collection may also be attributed to the availability of plant resources within their proximity or their engagement in activities that require bioenergy, such as cooking or heating. The relatively low representation of children in biomass fuel collection suggests that this task is primarily carried out by adults in the surveyed community. This finding aligns with the assumption that children are often not involved in energy-related activities due to safety concerns or the prioritization of their education and well-being. Nevertheless, further investigation is required to understand the specific reasons behind this minimal involvement of children in biomass fuel collection. The findings from the ethnobotany survey shed light on the gender dynamics and intergenerational patterns associated with biomass fuel collection for bioenergy purposes. Understanding the demographics and distribution of individuals involved in this practice is essential for developing effective policies and interventions that promote sustainable and equitable bioenergy utilization.

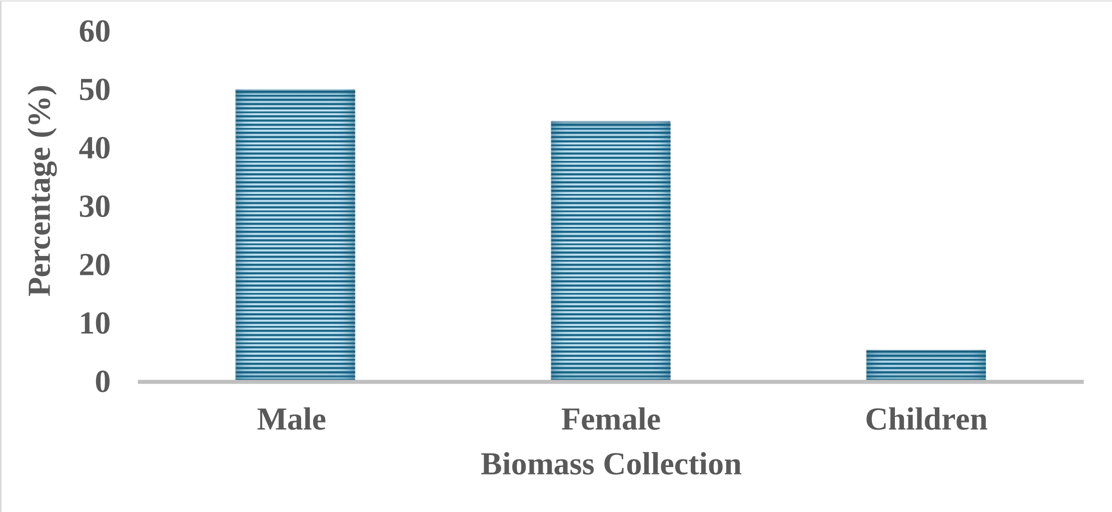

Figure 8. Distribution of respondents according to biomass fuel collection

4.6 The potential to obtain biomass fuel

The results indicated that a majority of the informants, approximately 89%, found it difficult to obtain biomass fuel, while a minority of 11% mentioned that it was easy (Figure 9). These findings shed light on the challenges faced by individuals in accessing this type of fuel.

One possible explanation for the perceived difficulty in obtaining biomass fuel is the average distance that informants had to travel to acquire it. The study found that the average distance to obtain biomass fuel was approximately 27.9 km. This distance can be a significant barrier for individuals, especially those living in towns, where the availability of biomass fuel may be limited. The remote location of biomass fuel sources can contribute to the perceived difficulty in accessing it. Informants residing far from these sources may face logistical challenges, such as transportation costs, time constraints, and the physical effort required to procure biomass fuel. These factors can discourage individuals from utilizing biomass fuel as an energy source, leading to a higher perception of difficulty in obtaining it. It is worth noting that the 10.9% of respondents who mentioned that obtaining biomass fuel was easy may reside in closer proximity to biomass fuel sources. These individuals may benefit from a more convenient and accessible supply chain, resulting in a perception of ease in obtaining biomass fuel.

The findings of this study highlight the need for measures to improve the accessibility of biomass fuel. Efforts should be made to reduce the average distance that individuals have to travel to acquire biomass fuel. This could involve establishing biomass fuel collection points closer to communities, promoting the cultivation of biomass feedstocks locally, or developing efficient distribution networks.

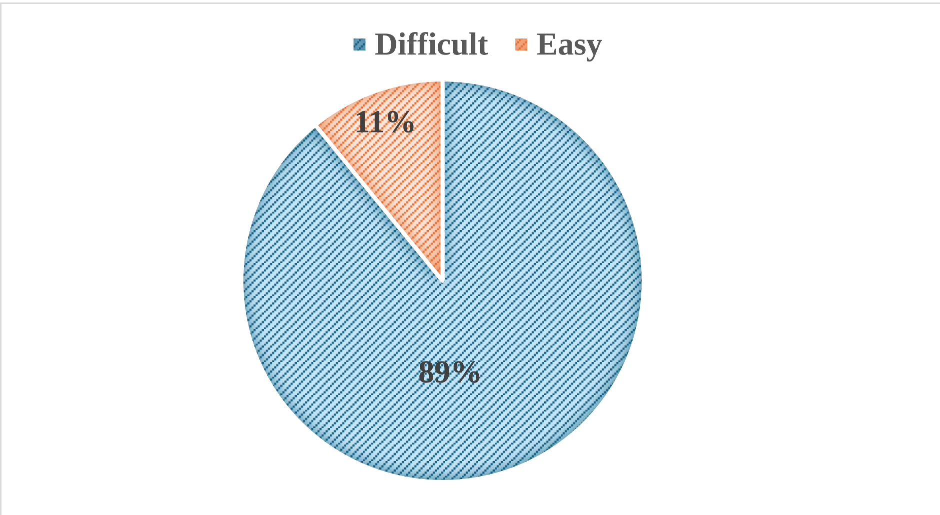

Figure 9. Possibility to obtaining biomass fuel in the study area

4.7 Tree species used for bioenergy

This study documented 18 indigenous tree species in 14 genera and 11 families used for energy purposes. The findings provide valuable insights into the diversity of tree species utilized for energy needs in the study area. Table 1 presents the distribution of energy tree species across different families. The plant family Fabaceae contributed the highest number of energy tree species, with a total of 9 species identified. This indicates the significance of Fabaceae in meeting the energy demands of the local communities. Fabaceae is a large family of flowering plants, commonly known as the legume family, and includes several species that have been traditionally used for their energy properties. These species may possess characteristics such as high calorific value, efficient burning properties, or easy accessibility, making them popular choices for energy purposes. Following Fabaceae, the family Combretaceae was found to contribute three energy tree species. Combretaceae is another diverse family of flowering plants known for their utilization in various applications, including energy production. The inclusion of multiple species from Combretaceae suggests its importance in meeting the local energy requirements as well. The identification of tree species from diverse families highlights the rich biodiversity of the study area and the local communities' reliance on various plant families for energy. This diversity can be attributed to the geographical location and ecological characteristics of the region, which provide a conducive environment for the growth of different tree species. It is worth noting that the study focused specifically on indigenous tree species used for energy purposes. This exclusion of non-indigenous species might have limited the total number of identified species. However, by focusing on indigenous species, the study emphasizes the sustainable use of local resources for energy needs, promotes conservation and reduces the potential ecological impact of introducing non-native species. The documentation of these energy tree species serves as a valuable resource for future studies, conservation efforts, and sustainable energy planning. Understanding the characteristics and energy potential of these tree species can aid in the development of efficient energy systems, resource management strategies, and informed decision-making processes. Further research could involve assessing the energy properties of these identified tree species, such as calorific values, combustion efficiency, and sustainability aspects. Additionally, studying the traditional practices and knowledge associated with the utilization of these species can provide insights into the local communities' cultural values and resource management practices.

Table 1. The common energy trees species in the study area

No	Family	Species	Local name
1	Arecaceae	*Hyphaene thebaica*	Dom
2	Asclepiadaceae	*Calotropis procera*	Oshar
3	Capparaceae	*Capparis decidua*	Tundob
4	Combretaceae	*Anogeissus leiocarpa*	Sahab
5	Combretaceae	*Combretum ghasalense*	Habil
6	Combretaceae	Guiera senegalensis	Khebash
7	Fabaceae	*Acacia mellifera*	Kiter
8	Fabaceae	*Acacia nilotica*	Sonut
9	Fabaceae	*Acacia senegal*	Hashab
10	Fabaceae	*Acacia seyal*	Talah
11	Fabaceae	*Albizia amara*	Arad
12	Fabaceae	Faidherbia0 albida	Haraz
13	Fabacea	*Dalbergia melanoxylon*	Abanus
14	Fabaceae	Prosopis chilensis	Miskeet
15	Fabaceae	*Vachellia tortilis*	Seyal
16	Rhaminaceae	*Ziziphus muritania*	Sider
17	Salvadoraceae	*Salvadora persica*	Arak
18	Zygophylaceae	*Balanites aegyptiaca*	Higlig

4.8 Bioenergy consumption patterns

The results of the survey indicate that among the total documented energy tree species, *Acacia seyal* is the most preferred species for domestic use, with 60% of the respondents stating their preference for this species (Figure 10). This finding suggests that *Acacia seyal* is widely recognized and utilized by households to meet their energy needs. The high preference for *Acacia seyal* could be attributed to its favourable qualities such as high energy content, availability, and ease of access. These characteristics make it a desirable option for domestic use, despite the presence of other species. *Calotropis procera*, on the other hand, was indicated as the second most preferred species for domestic use by 22% of the respondents (Figure 10). However, it is important to note that *Calotropis procera* is considered to be of lower quality compared to species like *Acacia seyal*, Acacia mellifera, and *Acacia nilotica*. The lower quality of *Calotropis procera* suggests that households may resort to using this species only when the preferred species are not readily available or have undergone significant degeneration. The finding indicates that the overexploitation of desirable species for energy needs has forced households to rely on lower-quality wood, including *Calotropis procera*. These results align with a UNEP report from 2008, which highlighted the overexploitation of local tree species for energy purposes. The report emphasized the depletion of forest resources and the consequent changes in the species traditionally used for energy. The current study's findings provide empirical evidence that supports the concerns raised by the UNEP report. The reliance on lower-quality species like *Calotropis procera* further emphasizes the urgent need to address the overexploitation of desirable tree species for sustainable energy use.

The study also investigated the species preferences of specific sectors, such as bakeries and brickmakers. Among the bakeries surveyed, *Acacia mellifera* emerged as the most preferred species, with 72% of the respondents indicating their preference for this species (Figure 10). This high preference for *Acacia mellifera* among bakeries suggests that it possesses qualities that are particularly well-suited for their energy requirements, such as high heat generation or desirable burning characteristics. *Acacia nilotica* was the second most preferred species among bakeries, with 16% of the respondents choosing it.

In the case of brickmakers, *Acacia nilotica* was the most preferred species, with 70% of the respondents indicating their preference for this species (Figure 10). This preference for *Acacia nilotica* among brickmakers could be due to its specific qualities that make it suitable for brickmaking processes, such as its ability to produce intense heat or long-lasting embers. Acacia mellifera and *Vachellia tortilis* were also preferred by brickmakers, albeit to a lesser extent, with 17% and 13% of respondents choosing them, respectively. The study's findings shed light on the preferences of different patterns regarding energy tree species. The high preference for specific species among households, bakeries, and brickmakers underscores the importance of understanding the qualities and characteristics of tree species in relation to their intended uses. This knowledge can guide efforts to promote sustainable practices in the energy sector, including the cultivation and conservation of preferred tree species, as well as the development of alternative energy sources to reduce the pressure on forest resources.

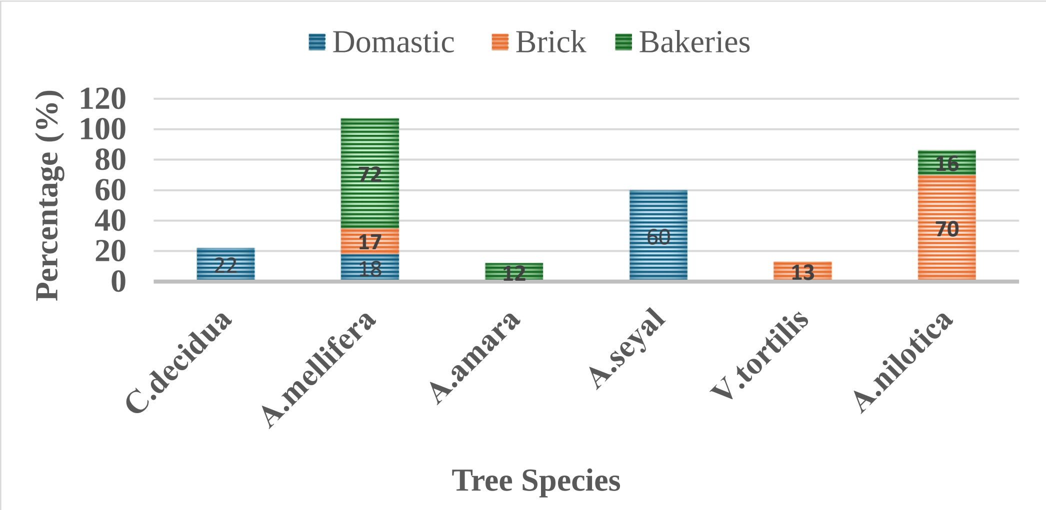

Figure 10. Preferred energy tree species according to utilization categories

Figure 11 presents the survey results regarding the biomass properties preferred by respondents. In the case of brickmaking, sustainable combustion was identified as the most desired property by 56% of the respondents. Sustainable combustion refers to the time between flame extinction and residence time. The longer the fuel combustion residence time, the more preferable it is for brickmakers. This finding aligns with prior research by Prior et al. (2018), who noted that brickmakers generally prefer long fuel combustion residence times. This preference can be attributed to the fact that bricks require a considerably longer baking time compared to bread. Brickmakers often utilize slow-burning fuels and occasionally opt for green wood instead of dead wood to achieve sustainable combustion. For baking, the survey results indicated that 52% of respondents valued haste ignition, while 27% prioritized low smoke. Bakeries require a fuel source that ignites quickly since baking bread typically does not require an extended cooking time. The preference for haste ignition aligns with the importance assigned to ignitability as stated in individual interviews. However, bakeries also expressed concerns about high smoke levels resulting from pollutant emissions such as NO_2 and SO_2. These emissions pose potential health risks to bakery workers, indicating a need for low smoke production during the baking process (Ahmed 2021).

Furthermore, the study revealed that certain tree species were assigned priority for energy production in the study area (Table 1). The identified species include *Acacia mellifera, Acacia nilotica*, *Acacia seyal, Vachellia tortilis, Albizia amara, Calotropis procera, Balanites aegyptiaca, Hayphaene thebaica,* and *Dalbergia melanoxylon*. These traditional energy tree species are likely preferred due to their suitability for biomass fuel production, such as their combustion properties, availability, and potential for sustainable harvesting. The findings of this study emphasize the specific requirements of different industries in terms of biomass properties. Brickmakers prioritize sustainable combustion, characterized by a long fuel combustion residence time, to ensure efficient brick baking. On the other hand, bakeries prioritize haste ignition for quicker bread baking but also emphasize the need for low smoke emissions to mitigate potential health risks. The identified tree species provide valuable insights into the local community's preferences for energy production, highlighting their knowledge of suitable biomass resources in the region.

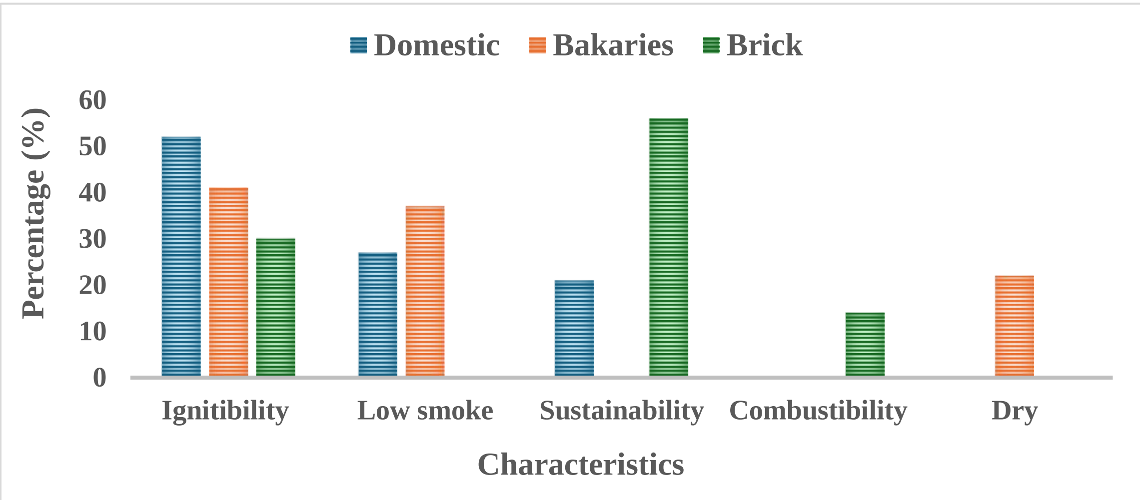

Figure 11. Preferred energy characteristics by utilization categories

4.9 Local perceptions and traditional knowledge

This section explores the local perceptions and traditional knowledge associated with tree species used as bioenergy.

4.9.1 Use value

The results of the use value (UV) analysis indicate that *Acacia mellifera* and *Acacia nilotica* are the most important energy tree species among the local tree species examined (Figure 12). The use value is a measure of the cultural importance and utilization of a particular plant species within a community or region. *Acacia mellifera* obtained the highest use value of 0.51, indicating that it is widely recognized and extensively utilized for its energy-related benefits. This finding suggests that the local community highly values *Acacia mellifera* as a significant source of energy. The species may possess desirable characteristics such as fast growth, high energy yield, and accessibility, making it a preferred choice for fuelwood, charcoal, or other energy purposes. The high use value of *Acacia mellifera* underscores its potential contribution to meeting the energy demands of the local population.

Similarly, *Acacia nilotica* obtained a substantial use value of 0.42, indicating its significant role as an energy tree species. While its use value is slightly lower than that of *Acacia mellifera*, it is still noteworthy and demonstrates the importance of *Acacia nilotica* in the local energy system. *Acacia nilotica* may possess specific traits such as high calorific value, ease of cultivation, or traditional cultural significance, leading to its extensive utilization for energy-related purposes. Comparing the use values of *Acacia mellifera* and *Acacia nilotica* with other local tree species, it is evident that these two species stand out as the most valued energy tree species in the area. Other local tree species may have lower use values, indicating comparatively lesser utilization for energy purposes. However, it is important to note that these results are specific to the studied region or community, and the importance of tree species may vary across different geographical locations and cultural contexts.

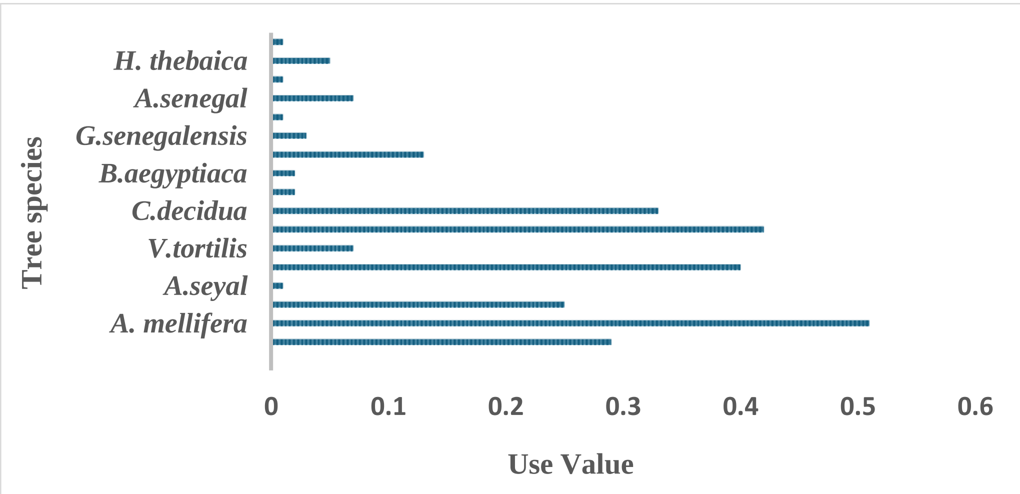

Figure 12. The use values (UV) of local energy tree species

4.9.2 Fidelity level

The results of Fidelity Level (FL) demonstrated that energy species that are more popular among local people tend to have higher FL values compared to less popular species. Among the energy species examined, *Acacia seyal* exhibited the highest FL value of 83%. This species is characterized by high combustibility, implying that it can readily catch fire and sustain combustion. *Acacia nilotica*, with an FL value of 69%, also showed a relatively high level of fidelity and combustibility. *Albizia amara*, on the other hand, had a lower FL value of 34% but was characterized by sustainable combustion. *Vachellia tortilis* had an FL value of 56%, indicating moderate popularity among local people. This species was found to possess characteristics of haste ignitability, implying that it can quickly catch fire. Acacia mellifera had a relatively lower FL value of 36%, suggesting it is less commonly used (Table 2). It was also characterized by haste ignitability. The physicochemical properties of the biomass varied among the different energy species. This variation is primarily influenced by biomass quantity, quality, moisture content, and aeration, all of which can impact the flammability of the species. For example, an increase in biomass quantity tends to enhance combustion, but it is likely to promote sustainability as larger fuel quantities take longer to burn.

Moisture content was identified as a key factor influencing ignitability. Species with higher moisture contents took longer to ignite and burned at a slower rate. This finding aligns with previous research by Simpson et al. (2016), indicating that moisture content plays a crucial role in the combustion behaviour of biomass. The study findings suggest that the popularity of energy species among local people is positively correlated with their FL values. Higher FL values indicate a greater frequency of use, likely driven by the desirable combustion characteristics of the species. Additionally, the physicochemical properties of biomass, such as quantity, quality, and moisture content influence the flammability and sustainable combustion of the energy species. These findings contribute to a better understanding of the factors affecting the selection and use of energy species by local communities, which can inform sustainable energy practices and resource management strategies.

Table 2. Fidelity level (FL) value and properties of commonly reported energy tree species

Species name	Properties category	Citation for properties	FL (%)
Acacia seyal	Combustibility	31	83%
Acacia nilotica	Sustainability	27	69%
Vachellia tortilis	Ignitibility	17	56%
Acacia mellifera	Ignitibility	17	36%
Albizia amara	Sustainability	8	34%

4.9.3 Factor informant consensus

The Factor Informant Consensus (FIC) analysis was conducted to determine the prevalence and importance of different biomass properties in the study area. The FIC results revealed that sustainable combustion scored the highest FIC value of 0.89, indicating that it is a highly prevalent and important property in the local context. This suggests that the informants consistently identified sustainable combustion as a crucial characteristic of biomass resources in the area. Following closely behind sustainable combustion, combustibility obtained an FIC value of 0.88. This indicates that combustibility is also highly valued and widely recognized as an important property of biomass resources by the informants. It implies that the availability of biomass with good combustibility is likely to be significant for various purposes, such as energy production or heating. Another notable property that received a high FIC value was ignitability, with a score of 0.85 (Table 3). This suggests that informants placed considerable importance on the ease with which biomass can be ignited. Biomass resources with high ignitability are likely to be preferred for applications that require quick and efficient ignition, such as cooking or starting fires for heating purposes.

The fact that sustainable combustion, combustibility, and ignitability were not only identified as the top recorded biomass properties preferred by informants but also obtained the highest FIC values further emphasizes their significance in the study area. These findings highlight the local community's recognition of the importance of sustainable practices and efficient utilization of biomass resources. The high FIC values obtained for these properties indicate a strong consensus among the informants, suggesting that these characteristics are consistently prioritized when assessing and selecting biomass resources. This consensus could stem from a variety of factors, including cultural traditions, local environmental conditions, and practical considerations for biomass utilization. It is worth noting that while sustainable combustion, combustibility, and ignitability were identified as the top properties preferred by informants, other biomass properties may also hold importance, albeit to a lesser degree. Future research could explore these additional properties to gain a more comprehensive understanding of biomass preferences in the study area. The results of the Factor Informant Consensus Analysis highlight the prevalence and importance of sustainability, combustibility, and ignitability as preferred biomass properties in the study area. These findings provide valuable insights for policymakers, resource managers, and other stakeholders involved in biomass utilization, enabling them to make informed decisions and prioritize the development and promotion of biomass resources that align with the preferences and needs of the local community.

Table 3. FIC values of traditional energy trees species properties in the study area

Properties categories	Number of species (*Nt*)	Number of properties report (*Nur*)	Consensus factor
Sustainable combustion	11	90	0.89
Combustibility	11	84	0.88
Ignitibility	9	54	0.85
Dry	3	9	0.75
Low smoke	5	12	0.64

4.10. Overexploitation

The results of the study indicate that there is a strong perception among respondents regarding the relationship between the increasing consumption of biomass fuel for energy purposes and the decline of forest area in the study area. Out of the total respondents surveyed, 90% acknowledged that the use of biomass fuel has led to a decline in forested areas, while only 10% of the respondents disagreed with this notion (Figure 13). The findings of the study suggest that the majority of the respondents perceive a direct link between the consumption of biomass fuel for energy purposes and the decline of forest area in the study region. This perception aligns with the widely acknowledged notion that the use of biomass fuel, such as wood and agricultural residues, can have adverse effects on forest ecosystems when not sustainably managed. The high percentage of respondents (90%) attributing the decline of forest area to the consumption of biomass fuel indicates a strong concern among the local population regarding environmental degradation. This concern may be rooted in their direct observations or experiences of witnessing the negative impacts of biomass fuel consumption on the surrounding forests. The findings also highlight the need for further investigation into the specific factors contributing to the decline of forest areas in the study region. While the respondents overwhelmingly associate biomass fuel consumption with forest decline, it is crucial to explore additional drivers, such as deforestation for other purposes (e.g., agriculture, urbanization) or inadequate forest management practices.

Moreover, the 10% of respondents who disagreed with the notion that biomass fuel consumption causes a decline in forest area offer an alternative perspective. It is essential to explore their reasoning further to gain a comprehensive understanding of the diverse opinions within the study area. Possible reasons for their dissent may include limited awareness of the environmental consequences, economic factors favouring biomass fuel consumption, or cultural practices that prioritize immediate energy needs over long-term forest conservation.

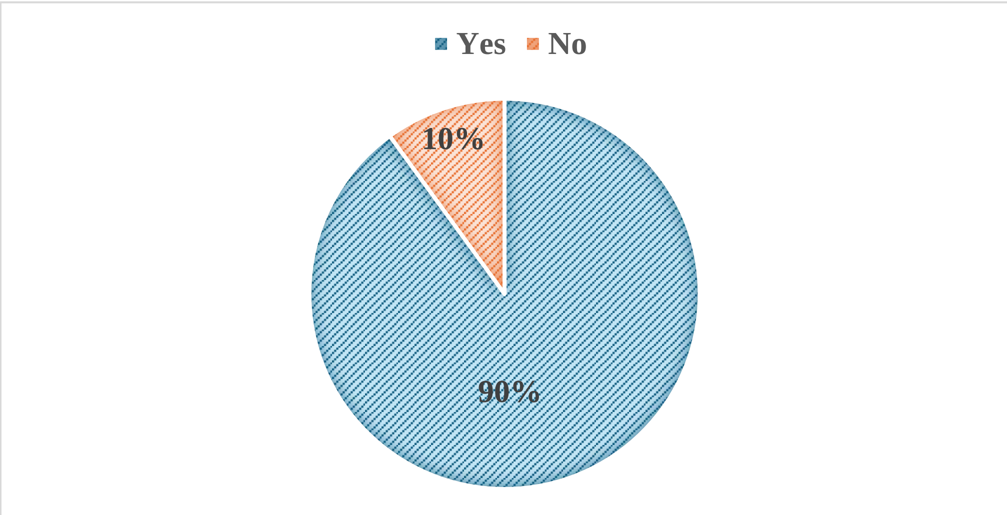

Figure 13. Respondents' perspective about biomass fuel overexploitation

4.11 Analysis of impact of sociodemographic factors on biomass fuel consumption model

Multiple linear regressions were used to assess the impact of the sociodemographic factors on biomass fuel consumers in the study area. Descriptions of the variables needed for consumers are listed in table 4.

Table 4. Description of the variables used for biomass fuel consumption model

Variables	Description	Type	Excepted sign
Age of respondents	Biomass fuel consumer Age	Continuous	+
Gender of biomass fuel consumer	Biomass fuel consumer Gender (male = 1, female = 0)	Dummy	-
Level of education	Biomass fuel consumer years of education	Continuous	+
Family size	Biomass fuel consumer Family size	Continuous	+

The multivariate regression analysis was conducted to examine the relationship between sociodemographic variables and biomass fuel consumption. The results of the analysis are presented in table 5. Overall, the coefficients of the sociodemographic variables aligned with the expected signs, indicating the direction of their impact on biomass fuel consumption. Among the four sociodemographic variables included in the analysis, family size had a positive and statistically significant effect on biomass fuel consumption. This finding suggests that as family size increases, there is a corresponding increase in biomass fuel consumption. This can be attributed to the larger energy needs of a larger household, leading to a greater reliance on biomass fuel sources. The positive coefficient indicates that for each unit increase in family size, there is a significant increase in biomass fuel consumption. On the other hand, the coefficients for gender were positive but not statistically significant, implying that gender does not have a significant impact on biomass fuel consumption. This suggests that both male and female individuals consume biomass fuel at similar levels, and gender alone does not influence the choice of fuel source. The coefficients for age and education level of biomass fuel consumers had negative effects on biomass fuel consumption, although these effects were not statistically significant. This implies that older individuals and those with higher education levels may consume slightly less biomass fuel compared to their counterparts. However, the lack of statistical significance suggests that these variables do not play a substantial role in explaining the variation in biomass fuel consumption.

The overall significance of the regression model, indicated by the F-value, suggests that the model as a whole is good for explaining the variation in biomass fuel consumption in the present data. This indicates that the sociodemographic variables included in the model collectively contribute to understanding the factors influencing biomass fuel consumption. The R-squared value of 50% suggests that the variables included in the model explain approximately half of the variation in biomass fuel consumption. This indicates that other factors not accounted for in the model, such as economic conditions or availability of alternative fuel sources, may also influence biomass fuel consumption in the study area. Considering the prevailing conditions in the south Darfur state, it can be concluded that family size has a significant impact on biomass fuel consumption, leading to a considerable reduction in the annual biomass amount. This finding highlights the importance of considering household size when addressing biomass fuel consumption and implementing strategies to promote alternative and sustainable fuel sources in the region.

Table 5. Estimated coefficients for biomass fuel consumption model in study area

Variable	Coefficient	t-statistics	Significant
Age of respondents	-0.01	-0.75	0.46^{ns}
Gender of biomass fuel collector	0.07	0.26	0.80^{ns}
Level of education	-0.11	-0.78	0.44^{ns}
Family size	0.09	2.47	0.01**
Constant	0.51	0.59	0.56^{ns}
N	92		
R	0.52		
F	3.03		
Prob > F	0.00		

ns = not significant; *, **, *** = significant (p = 0.05,0.01,0.000)

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In conclusion, this study has provided valuable insights into the utilization of bioenergy species in the study area and their significance in meeting the energy needs of the local population. The findings highlight the crucial role of traditional knowledge in the selection of energy species and the diverse preferences of different user groups. *Acacia seyal*, *Acacia mellifera*, and *Acacia nilotica* were identified as the most widely recognized and utilized species for biomass energy production, catering to the energy needs of domestic households, bakeries, and brick producers. These results are similar to those reported by Khider et al. (2012) and Hagar (2010). The study results underscore the importance of considering the specific properties of bioenergy species when designing conservation strategies, resource management plans, and sustainable development initiatives. *Acacia mellifera*, characterized by its ignitability, and *Acacia nilotica*, characterized by its sustainable combustion, were found to be favourable for biomass energy consumers in the study area. These species possess desirable properties for efficient and effective energy production, and their conservation should be prioritized to ensure the sustainable availability of biomass resources.

The heavy reliance on biomass fuels by the population in the study area highlights the significance of addressing the implications of this dependence on forest areas. The study indicates a strong perception among respondents regarding the negative relationship between increasing biomass fuel consumption and forest decline. The popularity and demand for the identified bioenergy species could potentially lead to degradation or even extinction if appropriate measures are not taken.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to inform conservation strategies, resource management plans, and sustainable development initiatives related to bioenergy utilization in the study area:

1. Further research and laboratory verification: To strengthen the results obtained in this study, it is recommended to conduct further research and laboratory verification of the characteristics and properties of the identified bioenergy species. This will provide a

more comprehensive understanding of their energy potential, combustion efficiency, and ecological implications, ensuring informed decision-making.

2. Rehabilitation of degraded species: Given the potential threats to the identified bioenergy species due to their high demand, it is crucial to prioritize the rehabilitation of degraded species through energy plantation and agroforestry programs. Such initiatives should focus on the restoration and sustainable management of the selected species to ensure their long-term availability and minimize the pressure on natural forests.
3. Community-based conservation and management: Engaging local communities in conservation and management efforts is essential for the success of bioenergy-related initiatives. Collaborative approaches should be adopted to involve local stakeholders in decision-making processes, promote their active participation in sustainable biomass resource utilization and create awareness about the importance of conservation.
4. Diversification of energy sources: While bioenergy plays a significant role in meeting the energy needs of the local population, it is crucial to encourage the diversification of energy sources. Promoting the adoption of renewable energy technologies, such as solar and wind power, alongside bioenergy, can help reduce the reliance on biomass fuels and mitigate the potential ecological consequences associated with their intensive use.
5. Policy interventions and incentives: Policy interventions and incentives should be developed and implemented to support sustainable bioenergy production and consumption. This can include the establishment of regulations for the sustainable harvest of bioenergy species, promoting efficient biomass conversion technologies, providing financial incentives for reforestation and agroforestry practices, and creating awareness campaigns to promote responsible energy consumption.

5.3 My New Scientific Results

The new scientific results of my dissertation can be summarized as follows:

Thesis 1. Indigenous tree species for energy in south Darfur state

This study pursued ethnobotany methods to gain knowledge from local people concerning the desired local energy species and document them scientifically in south Darfur. To determine the relative significance of each species, I used Use Value (UV) analysis. The findings indicated that *Acacia mellifera* (UV = 0.51) and *Acacia nilotica* (UV = 0.42) were the most beneficial tree species in terms of energy value when compared to other indigenous options. *Dalbergia melanoxylon* (UV = 0.40) and *Capparis decidua* (UV = 0.33) followed in importance.

Thesis 2. New scientific results on traditional bioenergy knowledge

I employed Factor Informant Consensus (FIC) and Fidelity Level (FL) to examine the traditional knowledge and practices associated with bioenergy use in south Darfur state.

Thesis 2.a. FIC analysis:

The FIC results revealed that sustainable combustion scored the highest FIC value of (0.89), indicating that it is a highly prevalent and important property in the local context. Following closely behind sustainable combustion, combustibility obtained an FIC value of (0.88). Another notable property that received a high FIC value was ignitability, with a score of (0.85). The fact that sustainable combustion, combustibility, and ignitability were not only identified as the top recorded biomass properties preferred by informants but also obtained the highest FIC values further emphasizes their significance in the study area.

Thesis 2.b. FL analysis:

The results of FL revealed that among the energy species that I examined, *Acacia seyal* exhibited the highest FL value of (83%). This species is characterized by high combustibility. *Acacia nilotica*, with an FL value of (69%), also showed a relatively high level of fidelity and combustibility. *Albizia amara*, on the other hand, had a lower FL value of (34%) but was characterized by sustainable combustion. *Vachellia tortilis* had an FL value of (56%), indicating moderate popularity among local people. This species was found to possess characteristics of haste ignitability.

Thesis 3. Sociodemographic factors and biomass fuel consumption

I conducted a multivariate regression analysis to examine the relationship between sociodemographic variables and biomass fuel consumption. I found that the sociodemographic variable coefficients had the predicted indications, showing their effect on biomass fuel consumption. Among the four sociodemographic factors analysed, family size positively and statistically significantly ($p < 0.01$) effects on biomass fuel consumption. The positive correlation shows that biomass fuel consumption increases significantly with family size. The coefficients for gender were positive but not statistically significant ($p < 0.80$), implying that gender does not have a significant impact on biomass fuel consumption. The coefficients for age and education level of biomass fuel consumers had negative effects on biomass fuel consumption ($p < -0.46$) and ($p < -0.44$) respectively, although these effects were not statistically significant.

5.4 Novelty and Significance

My research contributes to the existing ethnobotanical literature, particularly in the context of bioenergy and Sudanese plant diversity. By documenting the traditional uses of tree species for bioenergy, my study adds valuable data to the scientific knowledge regarding ethnobotany, bioenergy systems, and the cultural significance of plants in the study area. And it also provides insights into the tree species with bioenergy potential, enabling the identification of suitable species for afforestation and reforestation programs. Such initiatives can contribute to carbon sequestration, ecosystem restoration, and climate change adaptation strategies at local and regional levels.

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APPENDICES

University of Sopron, Faculty of
Forestry, and wildlife Management
Sciences

No.

Ethnobotanical Study on Some Tree Species Used as Bioenergy, Sudan

Biomass fuel consumption Questionnaire

Locality:…………………………………………
Unit:………………………………………
Village:………………………………….
Date of data collection:……………………
Name of data collector:……………………

The data contained in this questionnaire are confidential and used only for scientific research purpose.

Sociodemographic Information

Age: ☐

Sex:

Male: ☐ Female: ☐

The number of family members: ☐

Education level: ☐

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1. What energy sources do you use?

   Firewood: ☐ charcoal: ☐ LPG: ☐ Solar energy: ☐

   Others: ☐

2. How collects biomass fuel?

   Men: ☐ Women: ☐ Children: ☐

3. approximately how far is it to get firewood?.......KM

4. The possibility of obtaining firewood from the forest?

   Easy: ☐ Difficult: ☐

   If the answer is difficult, why?...
   ....
   ....

5. What are the suitable tree species for energy in the region?
…………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………………………

6. Does each tree species have a specific use? Yes: ☐ No: ☐
If yes, figure the following:

Tree species name	Preferably used in	The reason of use

7. What properties do you prefer in biomass fuel?
…………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………………………

8. Do you notice a decline in the forest area or the disappearance of some species:

Yes: ☐ No: ☐

If the answer is yes, what are the reasons?
…………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………………………

9. Approximately what is the appropriate amount of biomass fuel for your daily needs?........M^3