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Suitability of Crop Residues as Feedstock for Biofuel Production in South Africa: A Sustainable Win-Win Scenario

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Abstract: Alternative sources of energy are required for easing the burdens associated with the use of fossil fuels especially for African nations. There are barriers associated with the use of advanced biofuels such as immature technology, availability of reliable feedstock data, policy instruments among others in many African countries. The present study is aimed towards providing reliable feedstock generation data from 21 major crops produced in South Africa. By mining existing data on crop production and area harvested in literature, a technique called residue to product ratio (RPR) was used to generate data on the available feedstock for bioenergy production. Results showed that there is huge amount of available crop biomass (estimated at 13.5 Mt) in South Africa which can be tapped to produce biofuels. Cropped biomass from grains, oilseeds and deciduous fruits are estimated to produce 7 million tons of bio-oil via fast pyrolysis route or about 2 tons of bio-ethanol via biochemical route. The bulk of cropped biomass are estimated to contribute to a realization of the renewable energy target in South Africa by 2050. This study will assist government policy makers, waste managers, researchers as well as potential investors to make informed decision on biofuel generation in South Africa.

Key words: crop residues, biofuel feedstock, sustainable, biofuel production, win-win scenario

1 Introduction

The increase in global warming and its associated impacts on climate change due to fossil fuel combustion has created a sense of urgency among energy leaders, organizations and many different private and government institutions. There is need to find different measures to combat the climate change[1, 2]. According to Article 2, paragraph 1 in the Paris Agreement, there are two things which has to be done in order to mitigate climate change:

"(a) *Holding the increase in the global average temperature to well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change and*

(b) *Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production*"[3].

Renewable sources of energy such as Hydropower, Solar, Geothermal, Wind, Biomass, Wave and Tidal have been identified as tools which will help to realize those aspirations[4]. Of the above listed renewable sources of energy, only biomass can be converted in three different forms of energy carrier: solid, liquid, and gaseous biofuels[5]. Biofuels are used in different applications such as electricity production, heating, powering machines etc[6, 7]. The most common biofuels are Bioethanol and Biodiesel and to some extent Biogas[8]. Bioethanol is generated from starchy, sugar and lignocellulosic rich crop feedstock while biodiesel is generated from oil rich crop feedstock and biogas mainly from carbohydrate-rich biomass[9].

Bioethanol is produced worldwide mostly from corn and sugar. The leading countries in ethanol production are USA and Brazil[10, 11]. The production of biofuel from edible crops has been attributed to the price hikes of foodstuffs from

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2007-2008[11]. This has created a strong debate among scientist; some argue that producing biofuel from food crop feedstock is not ethical[12] considering the level of hunger around the world. While those in support, reject that point by saying that there is food wastage all over the world and they conclude that it is not the use of food crop to produce biofuel that causes hunger but an improper food management and distribution systems across the world[12].

Inspired by the food versus fuel debate, researchers across the world have started to investigate and assess alternative biofuel production feedstock in order to avoid the conflict of using food crop as potential source of generating biofuel. For instance, in 2015[13] assessed the potential lignocellulosic biomass or crop residues feedstock in China for producing biofuel and found that the theoretical amount of available crop residues equals to 930.8 Mt. This amount can be used to produce 44 Mt of bioethanol per year using biochemical conversion process or to generate 131 Mt of bio-oil per year using fast pyrolysis as a conversion route. In Iran[14], assessed the potential availability of lignocellulosic feedstock from agronomic and horticultural crops to produce biofuels via biochemical conversion route and the results revealed that about 11.33 Mt of crop residues can be collected to produce 3.84 Gigalitres of bioethanol. In South Africa, Pradhan and Mbohwa[15] did a research on development of biofuel in SA and concluded that the availability of reliable feedstock data is still a challenge. Our present review is meant to answer the above-mentioned challenge by evaluating the suitability of crop residues to produce biofuel in South Africa.

2 Literature Survey and Analysis

2.1 Energy Crops as Biofuel Feedstock

Feasibility of advanced biofuels lies on their feedstock availability at low cost. The supply chain of biomass feedstock from the point of collection (ex: in the farm) to the processing plant has significant impact on the price of the final product (fuel). Hence, crop residues, forest and wood wastes, food wastes to limit a list must be available and easily accessible at a reasonable cost including the transport cost. Energy crops grown on marginal or abandoned land can help to generate biomass feedstock at low cost and avoid direct competition for other crops. However, the oil content of any crop grown on less fertile soil will be lower than that of grown on well suitable soil[16]. This means that to have the same quantity of oil a huge amount of feedstock will be needed which will translate to a higher cost of feedstock. Technology in agriculture, like plant breeding and pest control, can result in higher production of food crops for the same unit of land, hence generating space to grow energy crops[17]. The quantity of land needed to obtain feedstock at a certain quantity of oil required is shown in Table 1.

2.2 Biomass resources in South Africa

2.2.1 Country profile

The Republic of South Africa is located on the southern tip of Africa and lies between latitude 22° to 35° S, and longitude 17° to 33° E[18] as shown in Fig. 1. The land area of South Africa is 1,214,470 square kilometres and water covers 4,620 square kilometres of area, and this ranks the country as 25th largest nation in the world with 1,219,090 square kilometres total area. SA is bordered in South East by Indian Ocean and South West by Atlantic Ocean. On the North West, it is bordered by Namibia and Botswana, in the North by Zimbabwe and Mozambique. Inside SA, there are two land locked countries, Lesotho and Swaziland.

South African climate is classified as semi-arid; the western part receives less than 200 mm of precipitation in a year. South Africa has a wider variety of climate as well as topography than most other countries in sub Saharan Africa[19], and it has a lower average temperature within the range of latitude, like Australia, because much of its interior plateau are at higher elevation. South Africa is regarded as a sunny country, and enjoy 8 to 10 hours of sunshine on an average day. The South Africa annual average rainfall is about 464 mm when compared to the global average of 860 mm. South Africa has an estimated population of about 57 million in 2017[19].

The population of South Africa constitute of 51% of female and 49% male, with a life expectancy of 67.3 years and 61.1 years respectively. The age pyramid of SA shows

Table 1 Land Area required feedstock production[17].

Type of plant	Plant capacity ranges, and assumed annual hours of operation	Biomass fuel required, (oven dry tonnes/year)	Truck vehicle movements for delivery to the plant	Land area required to produce the biomass (% of total land within a given radius)
Small pilot	15 000-25 000 l/yr, 2000 h	40-60	3-5/yr	1-3% within 1 km radius
Demonstration	40 000-500 000 l/yr., 3000 h	100-1200	10-140/yr	5-10% within 2 km radius
Pre-commercial	1-4 Ml/yr, 4000 h	2000-10 000	25-100/month	1-3% within 10 km radius
Commercial	25-50 Ml/yr., 5000 h	60 000-120 000	10-20/day	5-10% within 20 km radius
Large commercial	150-250 Ml/yr, 7000 h	350 000-600 000	100-200/day and night	1-2 within 100 km radius

Fig. 1 Continental location of South Africa[18].

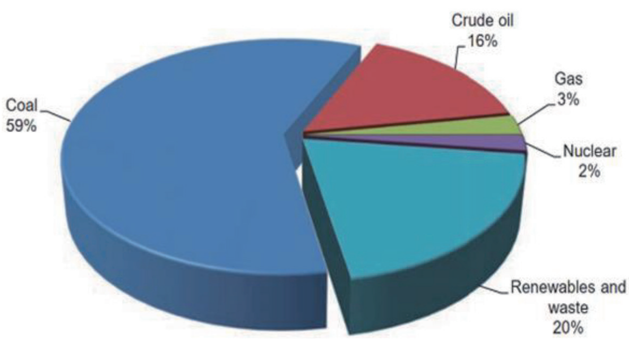

Fig. 2 South Africa Energy mix[21].

that 29.5% of the population is young and are above 15 years while 8.5% of the population is older and are above 60 years.

South Africa is an upper-middle-income economy. It is the world's largest producer of platinum, and a major producer of gold, and chromium. About 24 percent of Africa's gross domestic product (GDP) comes from South Africa with major industries comprising, mining, automobile assembly, textile, iron and steel, chemicals, fertilizers, ship repair, and food production[20].

2.3 Energy situation in South Africa

South Africa energy sector is dominated by coal which occupies 59%, followed by renewables and waste for a 20% share; crude oil comes on a third rank with 16%, while gas comes with 3% and then finally nuclear with 2% as shown in Fig. 2[21].

The country produced its liquid fuel from two technologies: Gas to Liquid (GTL) and Coal to Liquid (CTL) on 5% and 39% respectively as of 2015. The rest percentage came from crude oil[21]. Majority of petroleum products such as (petrol, diesel, residual fuel oil, paraffin, jet fuel, aviation gasoline, liquid petroleum gas) are synthetized or refined in the country. However, in order to meet South

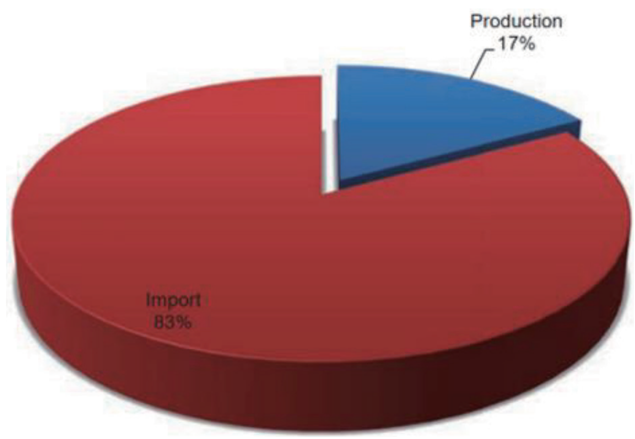

Fig. 3 South Africa's crude oil production and import in 2015[21].

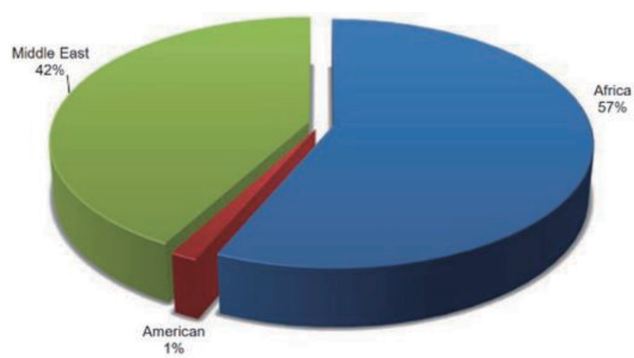

Fig. 4 South Africa's Crude oil imports by region in 2015[21].

Africa domestic energy demand, about 83% of petroleum products are imported from outside (Fig. 3). As shown in Fig. 3, in 2015 the country was heavily dependent on imported crude oil and the situation is likely to continue if no other alternatives to produce liquid fuels are provided. South Africa imports its liquid fuels from Africa, Middle

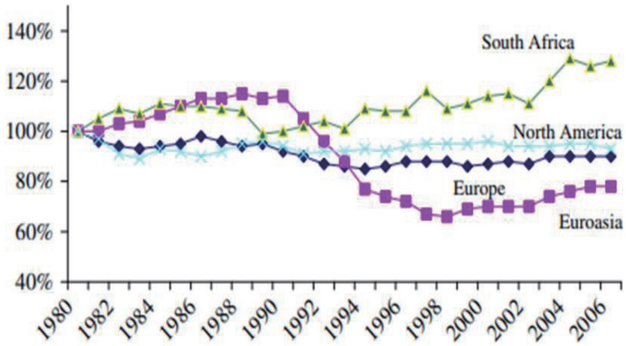

Fig. 5 CO_2 emission per capita from 1980-2006[21].

East and America with African countries occupying a big percentage (57%, Fig. 4) as of 2015.

The economy based on coal made South Africa in 2006 the highest GHG emitter country in the continent and in the world, whether the emissions is measured per capita or per energy intensity (one unit of energy used to produce one unit of good) as depicted in Fig. 5.

2.4 Why advanced biofuels in South Africa?

South Africa is the richest country among other African countries. The development of South Africa which is based on coal poses a high risk, not only to SA itself, but also to other countries in the continent as well the whole world in general. This is due to the amount of GHG emissions emanating from burning of coal. Once South Africa develops and accepts advanced biofuels technology, technology transfer with other African countries will be easy. The following points are essential for South Africa to consider advanced biofuels among other alternatives:

a) Like most African countries, South Africa is not an energy secured country. It imports crude oil to satisfy domestic consumption mostly in its transport sector.
b) Despite South Africa's many policies for promoting first generation biofuels, investors are still not convinced for investing in this sector mostly because of fear involving debate on energy versus fuel. Only small producers are in the sector and they don't target to produce fuel to satisfy South Africa transport sector[15].
c) Boosting the agricultural sector by helping farmers to gain a bonus from their crop residues which otherwise are considered as waste for rural farmers.
d) Waste management: municipal solid waste will be handled easily.
e) Feeding animals: left overs (cake) a byproduct which remain after extracting fuel is very rich in nutrients which is a good fodder for animals.
f) Pollution reduction: renewable fuel will be generated which will substitute petroleum products in transport sector.
g) Job creation: the sector has job creation potential compared with jobs obtained in the refinery of crude oil. It was estimated in Thailand that ethanol production generates 17-20 times more jobs than petrol and 90% jobs was concentrated in agriculture sector[15].
h) The technology will not compete with food as opposed to first generation one and 14% of land is underutilized hence growing energy crops will not have direct impact on food crops, also marginal land can be used.
i) South Africa has a well-known rich history in R&D for technologies regarding the conversion of cellulosic biomass which started in 1970s when Council for Scientific and Industrial Research (CSIR) began funding a study program to develop a technically and commercially viable process to convert bagasse into ethanol[15].
j) Energy diversification: Convention fuel reserves are predicted to be depleted soon, so by introducing new technology of generating fuel will help to avoid depletion surprise.
k) South Africa has clear policy regarding biofuels, it was developed by biofuel task team and ratified by the government in 2007 where the blending mandate was put on 2% with petroleum product. The policy has been revised in 2012 and allowed 5% blending of biodiesel with diesel and 2% to 10% blending of ethanol with petrol[15].

2.5 Source of Advanced Biomass Feedstock in South Africa

Advanced biofuel feedstock also known as lignocellulosic feedstock include: crop residues, forest wastes, municipal solid wastes, energy crops (woody and herbaceous). The following major crops are grown in South Africa as presented in the yearbook of the Department of Agriculture[22] which have potential for generating many residues as advanced biofuel feed stock which can benefit biofuel industry in South Africa.

2.5.1 Grain crops

2.5.1.1 Maize

Maize is the most important crop grown in SADC region. Maize contains most important carbohydrates and it is the food for both human and animals. South Africa is the leading producer of maize in the region. Generally, maize production in SA ranges between 12 million tons to 14 million tons per annum[22]. It is grown mainly in North West, the Free State and Mpumalanga. Two types of maize are grown: white for human consumption and yellow for animal consumption. The planting season for maize in South Africa starts during late spring/early summer. South Africa is a net exporter of maize. The residues generated when harvesting and processing maize are: stalks, cobs, leaves and husks[22, 23]. South African government has excluded the use of grain from maize in biofuel production[24].

2.5.1.2 Wheat

The second most important grain crop, after maize, produced in South Africa is Wheat. It is a very important crop because it plays a big role in the national food security. It is used mainly for producing bread, biscuits, breakfast cereals, and rusk for human consumption and the rest is used as animal feed. Wheat is also used for non-food uses such as adhesives and industrial uses as starch on coatings. South Africa is an importer of wheat. The planting season is between April and June in the Western Cape and between May and end July in Eastern Free State province. In South Africa, the wheat marketing season starts early in the October and ends with September of the following year. Residues generated during harvesting and processing of wheat are called straw[22, 23].

2.5.1.3 Barley

Barley is the third important grain in SA after maize and wheat. Production of malting barley in South Africa is concentrated in the dry land of Southern Cape which receives precipitation of at least 350 mm because it is not economical for other areas where precipitation falls below 350 mm. The concentration of malting barley in Southern Cape has associated advantages like easy transportation and facilitating storage, control, extension and research which otherwise implies a high costing factor. Other areas where barley is found in small quantity are North West, Limpopo and Free State. The growing season of malting barley in South Africa is April to October. The use of barley is in the production of malt for brewing beers, animal feed and pearl barley[22].

2.5.1.4 Sorghum

Sorghum is an African indigenous crop. There exist two types of sorghum: sweet and bitter but sweet cultivars is the most preferred type. Sorghum does not require a lot of rainfall to grow which makes it a good candidate for arid and semi-arid climate like that of South Africa. It is grown in Northern Cape, Western Free State, Mpumalanga, the drier parts of North West and Limpopo provinces. The planting period of sorghum in South Africa is between mid-October and mid-December. About 60 thousand hectares was projected for growing sorghum in 2017/2018. The national consumption is around 200 thousand tons per annum[22]. South Africa is a net importer of sorghum. Sorghum Stover is the name of residue after the grain has been removed.

2.5.1.5 Dry Beans

Dry beans is preferred because of its high-water-use efficiency and its contribution to soil quality by fixation of nitrogen in the soil[22]. It is a feedstuff for animals and plays a major role in food security as it contains much protein. It is grown mainly in the Free State, KwaZulu-Natal, Limpopo, North West and Northern Cape provinces. South Africa is a net importer of dry beans[22].

2.5.2 Oilseeds

2.5.2.1 Groundnuts

In South Africa, groundnuts are grown mainly in the Free State, North West and Northern Cape. It is also grown in Limpopo, Mpumalanga and KwaZulu-Natal in small quantities. The planting period is mid-October to mid-November. The marketing season starts in March and ends in February of the following year. Groundnuts are rich in protein. Groundnuts can be used mainly to produce oil for cooking and making peanuts butter[22].

2.5.2.2 Sunflower seed

It is produced mainly in Free State and North West provinces. Limpopo. Mpumalanga and Gauteng provinces also grow sunflower seed but they come after the above-mentioned provinces. South Africa is ranked as the 10th largest producer of sunflower seed in the world. The growing period for sunflower seed is from November to December in Eastern parts and up to middle January in the Western part. Sunflower performs well under dry conditions compared to other crops and it is planted in marginal areas in South Africa. The oil produced from sunflower are used for cooking. The oilcake as a byproduct can be used as animal feed. In 2017 the global contribution of South Africa in sunflower was 850 thousand tons in 46.1 million tons[22]. South Africa remains to be a net importer of sunflower seed.

2.5.2.3 Macadamia nuts

In South Africa, 180 hectares (ha) is reserved for macadamia production with 80 ha harvested for export. The crop is supported by Department of Agriculture, Forest and Fisheries (DAFF) together with Eastern Cape Department of Rural Development and Agrarian Reform as a private-public partnership. It has created 110 permanent jobs[22]. There is a plan to expand the development of macadamia in Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo provinces.

2.5.2.4 Soya beans

Soya beans are grown in Mpumalanga, the Free State and KwaZulu-Natal in large quantities. It is also available in Limpopo, Gauteng and North West in lower quantities. It is a difficult crop to grow and not all areas are suited for it. Soya beans contain enough protein and it's used to produce milk for under-nourished children. In 2017, soya beans were planted on 574 hectares[22]. The projection shows that 900 hectares will be required which will give 2.1 million tons in 2026. The growing period of soya beans in South Africa is November to December. The by-product of soya beans (oilcake) is a good candidate for advanced biofuels.

2.5.2.5 Canola

Canola is an oil seed introduced in the early 1970s using traditional plant breeding techniques by Canadian plant breeders. Its seeds have very low level of saturated fat. About 99% of the canola crop in SA is concentrated in Western Cape Province, especially in the Southern Cape.

2.5.2.6 Sugar cane

Sugar cane in South Africa is grown predominantly in KwaZulu-Natal. It is also found in Mpumalanga and Eastern

Cape. The sector comprises 29 000 registered sugarcane growers[22]. Sugar cane is ratoon crop and when it has grown, it gives up to 10 new cane stalks before it can be replaced. South Africa sugar industry is ranked among first 15 in the world. There exist 14 sugar mills located nearly where cane is grown because after harvesting the cane, sugar can deteriorate only after 3 days. This makes sugar cane to create jobs in deep rural areas on estimate of 79 000 direct jobs which represent 11% of total agricultural workforce in South Africa. The residues from cane farming fields are mainly tops and leaves while the one from mills are bagasse and molasses.

2.5.3 Deciduous fruit

This industry in South Africa comprises includes fresh, dried and canned fruit for local consumption and export. Deciduous fruits grown in South Africa include apples, pears, apricots, peaches and nectarines, plums and sloes, grapes, figs and cherries. Deciduous fruits are found largely in Western Cape, however for past 2 decades, the Northern Cape and Eastern Cape provinces[22].

2.5.4 Vegetables

Vegetables in South Africa constitute what is called perishable export industry and comprises with: tomatoes, onions and cabbages. Vegetables are produced countrywide. Sometimes potatoes are considered as vegetables but not constituent of perishable industry. Potatoes are produced in 16 distinct potato-production regions in South Africa spread throughout the country. The main regions where potatoes predominate are situated in the Free State, Western Cape, Limpopo and Mpumalanga[22].

3 Lignocellulosic Biomass Properties and Available Technologies

3.1 Properties

Plant biomass is composed by three important elements: cellulose, hemicellulose and lignin as shown in Fig. 6. These are the main elements found in plant, also plant biomass constitutes other elements like protein, pectin, non-structural material as sugars and inorganic minerals[25].

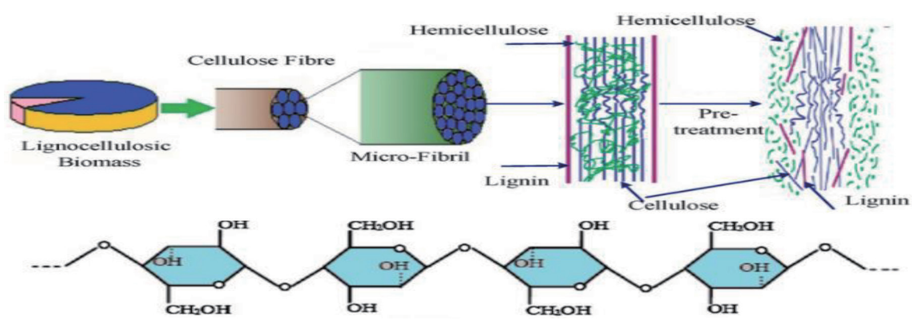

Fig. 6 Different plants have different amount of cellulose, hemicellulose and lignin.

Table 2 Cellulose, hemicellulose and lignin in selected agriculture waste[25].

Lignocellulosic biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Corn cobs	45	35	15
Cotton seed hairs	80-95	5-20	0
Grasses	25-40	35-50	10-30
Hard wood stems	40-55	24-40	18-25
Leaves	15-20	80-85	0
Newspaper	40-55	25-40	18-30
Nut shells	25-30	25-30	30-40
Paper	85-99	0	0-15
Softwood stems	45-50	25-35	25-35
Solid cattle manure	1.6-4.7	1.4-3.3	2.7-5.7
Sorted refuse	60	20	20
Waste papers from chemical pulp	60-70	10-20	5-10
Wheat straw	30,39.2,35.1	50,26.1,25.6	15,21.1
Maize Stover	37.5	30.0	10.3,8.4
Rice straw	44.3,38.9	33.5	20.4
Rice husks	34.4,38.3	29.3	19.2
Sugarcane bagasse	45.0	20.0	30.0

Table 3 Types of pre-treatment for lignocellulosic biomass[25].

Group	Method/Process	Types	Possible change in biomass and notable remarks
Mechanical/Physical	Grinding/milling	Hammer milling, Ball milling, Two-roll milling, Colloid milling Electroporation, (Vibro milling)	Due to size reduction accessible surface area and pore size increases. Thus, decreases cellulose crystallinity Lignin cannot be removed. Most of the methods require high energy. No chemical requirement.
	Irradiation	Gamma ray, Electron beam Microwave	Leads to cleavage of β-1,4-glucan bonds and gives a larger surface area and a lower crystallinity.
	Others	Hydrothermal, High pressure streaming Expansion, Extrusion, Pyrolysis	The cellulose component of the lignocellulose materials can be degraded to fragile fibers and lower molecular weight oligosaccharides and cellobiose. This method is too expensive. Cellulose rapidly decomposes to gaseous products and residual char when biomass is treated at temperatures greater than 300℃
Chemical and physiochemical	Alkali.	Sodium hydroxide, Potassium hydroxide Calcium hydroxide, Magnesium hydroxide Ammonia, Ammonium sulphate.	Efficacy order of alkali (NaOH >KOH >$Mg(OH)_2$ and $Ca(OH)_2$)
	Acid	Sulphuric acid; Hydrochloric acid Phosphoric acid	Increase in accessible area, partial or nearly complete delignification; Decrease in cellulose crystallinity; Decrease in degree of polymerization; Partial or complete hydrolysis of hemicellulose.
	Gas	Choline dioxide; Nitrogen dioxide Sulphur dioxide	
	Explosion	Steam explosion, Ammonia fiber explosion, CO_2 explosion, SO_2 explosion	These methods are the most effective and promising processes for industrial applications and usually have rapid treatment rate and need harsh conditions
	Oxidizing agents	Hydrogen peroxide; Wet oxidation Ozonolysis	
	Solvent extraction of lignin	Ethanol-water, Benzene-Water, Butanol-water, Ethylene glycol, Swelling agents	
Biological	Fungi and actinomycetes		Delignification and reduction in degree of polymerization of cellulose and partial hydrolysis of hemicellulose. Low energy requirements and mild environmental conditions are the main advantages. However, the pretreatment rate is very low.

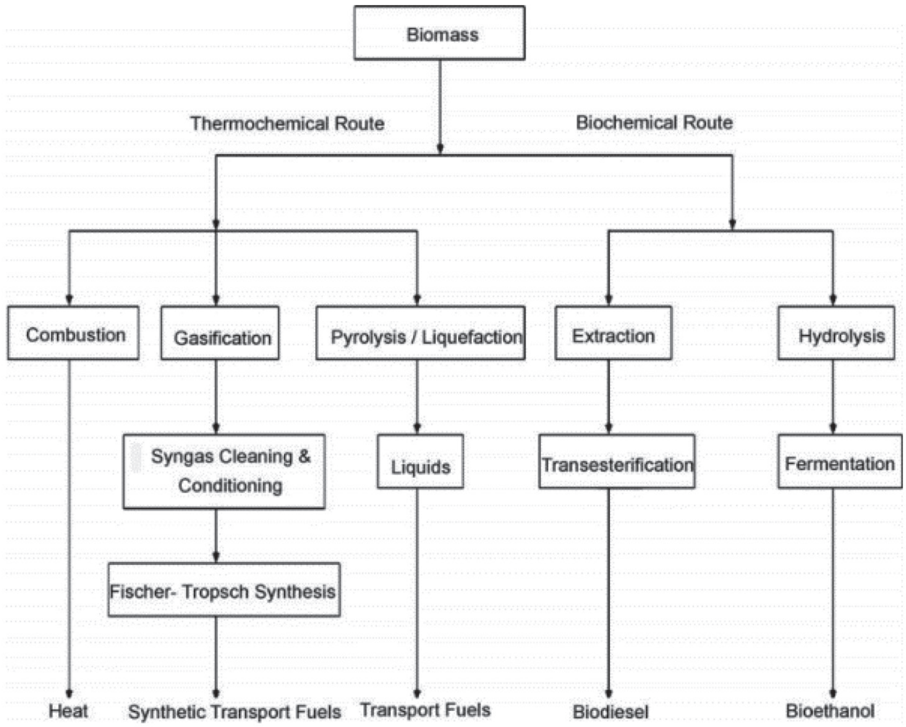

Fig. 7 Thermochemical and biochemical biomass conversion technologies[26].

Table 2 presents some common agricultural biomass and their proportion in lignin, cellulose and hemicellulose.

3.2 Pretreatment methods for lignocellulosic biomass

Pretreatment of biomass is necessary to be able to convert lignocellulosic biomass into appreciable amount of sugars for subsequent conversion processes. Different methods exist depending on which is appropriate for certain conversion (Table 3).

3.3 Conversion technologies for advanced biofuels

There are two main routes to produce biofuels from lignocellulosic biomass: Thermo-chemical, also known as biomass to liquid (BTL) and biochemical[26] (Fig. 7). Biochemical route involves the use of enzymes and other micro-organisms to break down cellulose and hemicellulose components of the feedstock.

The breakdown results in the production of sugars prior to their fermentation to ethanol. The thermo-chemical route also known as biomass-to-liquids (BTL) employs pyrolysis/gasification technologies to produce a synthesis gas ($CO + H_2$) referred to as Syngas. The syngas form the basis from which a wide range of long carbon chain biofuels, such as synthetic diesel, aviation fuel, or ethanol, can be produced using the Fischer–Tropsch conversion method[17]. Different feedstock requires different conversion technologies in order to produce a certain type of biofuel (e.g. bioethanol) (Table 4). The very recent studies of Sher *et al.*[27] presented an in depth synthesis of the thermal and kinetic analysis of diverse biomass fuels under different reaction environment as potential for diverse biofuels for use.

Hai *et al.*[28] further presented an assessment of biomass energy potential for willow woodchips in a fluidized bed gasifier application.

4 Methodology

4.1 Determining potential availability of crop residues

The protocol used to assess the availability of crop residues for biofuel production is shown in Fig. 8.

In order to characterize crop residues available for biofuel production in SA, crop production and harvested area have been taken into account. To ensure data quality, average production for a 10-year consecutive period (2008-2017) was chosen as our study time frame. The information on crop residues most of the time is not available. However, the information on crop production and area harvested is available. To generate data on crop residues, a technique called residue to product ratio has been used. Empirical literatures from Eisentraut and Escalante *et al.*[30, 31] provided the following relations (Equations 1-3) which was useful in generating data on crop residues:

$$A_{TR} = A_C \times RPR \quad (1)$$

Where, A_{TR}, Residue annual total amount in tonnes; A_C, Crop annual amount in tonnes; RPR, Residue to Product ratio.

Table 4 Technologies used to produce ethanol and practical case examples[29].

Feedstock	Technology	Company, location
Corn Stover, wheat straw, milo stubble, switch grass	Enzymatic hydrolysis, fermentation, thermochemical	Abengoa, Madrid
Wood, citrus waste, urban green waste	Thermochemical, gasification, fermentation	ALICO, Florida
Urban green waste, wood chips, car tires, plastics	Thermochemical, gasification, fermentation	Bioengineering resources, Arkansas
Wood construction waste	Enzymatic hydrolysis, fermentation	Bioethanol Japan, Osaka
Hay, grass, manure fibers, straw, paper	Enzymatic hydrolysis, fermentation	Biogasol, Lyngby
Urban trash, rice, and wheat straw	Concentrated acid hydrolysis, fermentation	BlueFire Ethanol, Irvine
Corn Stover	Enzymatic hydrolysis, fermentation	China Resources Alcohol Corporation, ZhaoDong City
Cellulosic biomass	Gasification	CHOREN
Sugarcane bagasse	Thermochemical, gasification, modified Fisher-Tropsch	ClearFuels Technology, Hawaii
Waste rice straw, rice husks	Enzymatic hydrolysis, fermentation (*Klebsiella oxytoca* and *E.coli*)	Colusa Biomass Energy, California
Spent pulping liquor	Alcohol sulfite cooking liquor to fractionate softwood chips, fermentation	Flambeau River Bio-refinery, Wisconsin
Wheat straw, barley straw, corn Stover, switch grass, rice straw	Enzymatic hydrolysis, fermentation (*Trichoderma reesei*)	Iogen , Ottawa
Wood chips, corn Stover, switch grass	Enzymatic hydrolysis, fermentation	Lignol Innovations, Burnaby
Switchgrass, wood	Enzymatic hydrolysis, fermentation, (*Thermoanaerobacterium saccharolyticum*)	Mascoma, Cambridge, Massachusetts
Corn fiber, corn cobs	Enzymatic hydrolysis, fermentation	Poet/Dupont, Delaware
Wood and vegetative wastes	Thermochemical	RangeFuels
Paper	Gasification	UPM, Finland
Sugarcane bagasse, wood	Enzymatic hydrolysis, fermentation	Verenium, Cambridge, Massachusetts

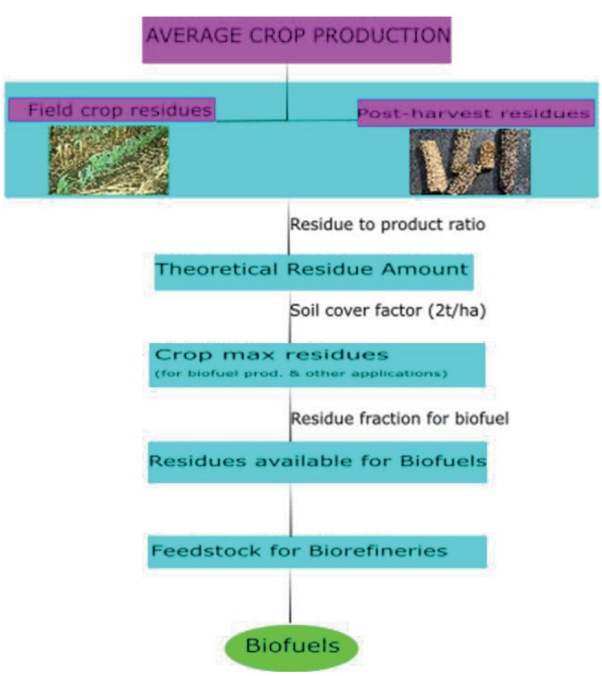

Fig. 8 Protocol for biofuel residue assessment.

In order to avoid indirect Land Use Change (iLUC) it is essential to leave some crop residues in the field for land covering purposes so that organic content in the soil is maintained. The quantity of residues, which can be left in the field, depends on the type of the crop, but an estimate of two to four tons per hectare is usually made. Therefore, the maximum amount available residue for producing biofuels can be calculated as:

$$A_{MB} = A_{TR} - S \times F_c \qquad (2)$$

Where, A_{MB}, Biomass maximum annual amount for biofuel production in tons; S, Harvested area in ha; F_C, Field cover factor in t/ha. Bearing in mind that some losses occur during crop residue handling and transportation from the field to production plant, also other uses of crop residues like bedding, animal feeding and other usage[32] have been taken into account in order to avoid indirect conflict which can arise when all residues are used to generate biofuels. Hence, it was assumed that only a fraction from maximum available residue can be used to produce biofuel in a sustainable way as illustrated in the following relation (Equation 3).

$$A_{CB} = f_{cB} A_{MB} \tag{3}$$

Where, A_{CB}, Collectable biomass total amount as feedstock for bio-refineries in tonnes; f_{CB}, Fraction of collectable biomass.

5 Results and Discussion

The following results were obtained after collecting and analyzing the information from literature.

5.1 Data on residues

Table 5 shows the calculated theoretical residue value from average crop production in South Africa from 2008 to 2017 according to Food and Agriculture Organization[19] of the United Nations. The results showed that the highest average crop production in SA for the period 2008 to 2017 is Sugarcane (~17 Mt) followed by Maize with approx. 12 Mt and then Potato (~2 Mt), Wheat (~1.7 Mt) in that order. Figs and Cherries were the least produced crops in SA within the studied period with estimates of 200 and 300 tons respectively. Apples (~0.8 Mt) and Soybeans (~0.7 Mt) are also highly produced in SA in contrast to Rice with low production level (~3000 t). SA being a water scarce country with an average annual rainfall of about 464 mm may not be suitable for rice production which requires a marshy environment to thrive. The main reason behind the high production of maize in South Africa is that it is the principal food crop for most households. In terms of biofuel production, the SA government has excluded maize from being used as a bioenergy crop to avoid fuel vs. food debate issues[24]. However, its residues can be used to produce advanced biofuels.

Grain crops (maize, wheat, barley, rice and dry beans) contribute more residues than other types of crop. Of the ~43 Mt average residues produced in SA, ~32 Mt comes from grain crops followed by sugar cane with an average contribution of ~6 Mt. Next to sugar cane are oil-crops (ground nuts, sunflower seeds, soybeans) and vegetable crops (potato, tomato, cabbages) with ~3 Mt and 1 Mt respectively. The least contributor in average residue production is deciduous fruits (apples, pears, peaches and nectarines, plums and sloes, grapes, figs and cherries) with an estimated 0.8 Mt.

Of the grain crops in South Africa, maize is the major contributor of residues with ~28 Mt out of ~32 Mt due to its importance in SA as a major staple food cultivated in large areas (Department of Agriculture 2017/2018). Among the oil crops, sunflower seeds contribute more than groundnut and soybeans with ~2 Mt out of ~3 Mt. Potato is the main contributor of residues among the vegetables with ~0.5 Mt out of ~1 Mt.

The highest theoretical residues in South Africa is generated from maize (~28 Mt) followed by sugarcane (~6 Mt)[10, 11]. The 3rd, 4th and 5th theoretical residues generation came from wheat (~3 Mt), sunflower seeds (~2 Mt) and soybeans (~1 Mt) respectively. The least amounts of residues are generated from figs and cherries with an infinitesimal contribution to the residues in total.

A careful look at the calculated theoretical crop residues highlights the importance of residue to product ratio (RPR). Some crops may produce more residues than others even if they have the same amount of production in tons. For example, sugar cane has a high production amount but its RPR is very small (~0.35) compared to sunflower (~3.0).

Of the 21 major crops cultivated in SA, only 10 have the potential to generate large number of residues for biofuel production and other applications (Fig. 9). Negative values for figs and cherries indicate that those crops cannot contribute meaningfully to the collectable residues for producing biofuels.

Using Equation 2 and by setting the field cover factor by 2 tons/ha, the maximum annual collectable biomass amount was estimated at approx., 34 Mt as illustrated in Table 5.

As discussed in Equation 3, all available biomass cannot be used for producing biofuels because beside biofuel production, biomass has many other applications. In order to avoid conflict of interest, we assumed that only 40% of maximum collectable biomass (~34 Mt) could be used to produce biofuels. The calculated amount for biofuel production is approximately 13.5 Mt.

5.2 Biofuel potential from agricultural residues

According to (Ji 2015), one ton of crop residues is needed to produce 0.17 to 0.20 t of bio-ethanol. Hence, 13.5 Mt of residues can be calculated from 19 potential crops. In the present study, biochemical and fast pyrolysis conversion routes[13] was used to generate bioethanol as follows:

a) Using biochemical conversion routes, the average value (~0.18 t) of the produced bioethanol range (0.17 to 0.20 t) could be used to generate an estimated 2 million tons of bio-ethanol from 13.5 Mt of crop residues per annum.

b) Similarly, employing the fast pyrolysis route for bio-oil, two tons of crop residues are needed to generate one ton of bio-oil[13]. Hence, from 13.5 Mt of residues (~7 million tons of oil equivalent) could be generated per year.

5.3 Environmental Impact of Conversion processes

Although sustainable production of biofuels from biomass and agricultural feedstocks remains significant in South Africa's renewal energy demand, it also hugely correlates to the levels of agricultural production. Environ-

Table 5 Theoretical residue from average crop production (2008-2017).

Types	Name of crop	Area harvested (ha)	Average crop production (tons)	Residue to product ratio	Theoretical residue generated (tons)	Field cover factor tons/ha	Collectable residue (tons)
Grain crops	Maize (Stalk)	2 573 760.00	12 065975.60	2.30[32)]	27 751 742.00	2[14]	22 604 222.00
	Wheat (Stalk)	552 848.50	1 794 300.00	1.80[32)]	3 229 740.00	2[14]	2 124 043.00
	Barley (Straw)	83 101.50	277 550.00	1.30[32)]	360 815.00	2[14]	194 612.00
	Sorghum (Stalk)	67 944.50	177 320.00	2.26[35)]	400 743.20	2[14]	264 854.20
	Rice (Straw)	1 152.20	3 045.20	1.70[35)]	5 176.84	2[14]	2 872.44
	Dry beans (Straw)	456 170.00	58 762.50	1.70[35)]	98 896.25	2[14]	7 662.25
Oil crops	Ground nuts (Straw)	50 242.50	68 758.00	2.30[32)]	158 143.40	2[14]	57 658.40
	Sunflower seeds (Stalk)	572 705.00	722 600.00	3.00[32)]	2 167 800.00	2[14]	1 022 390.00
	Soybeans (Straw)	438 805.00	758 450.00	1.70[32)]	1 289 365.00	2[14]	411 755.00
Sugar crop	Sugarcane (Top and leaves)	265 414.00	17 311 711.20	0.35[32)]	6 059 098.80	2[14]	5 528 270.80
Deciduous fruits	Apple (Pruning)	22 781.90	835 075.80	0.47[35)]	392 485.62	2[14]	346 921.82
	Pears (Pruning)	22 219.10	374 176.50	0.45[35)]	168 379.42	2[14]	123 941.22
	Apricots (Pruning)	477.80	42 649.30	0.35[35)]	14 927.26	2[14]	13 971.66
	Peaches and nectarines (Pruning)	10 258.30	171 463.70	0.35[35)]	60 012.30	2[14]	39 495.70
	Plum and Sloes (Pruning)	7 628.10	70 351.60	0.35[35)]	24 623.06	2[14]	5 889.34
	Grapes (Pruning)	115 851.40	1 881 453.40	0.07[35)]	122 294.47	2[14]	99 123.67
	Figs (Pruning)	67.11	205.12	0.45[35)]	92.30	2[14]	−41.92
	Cherries (Pruning)	160.60	344.30	0.83[35)]	285.77	2[14]	−35.43
Vegetables	Potato (Stems)	62 471.30	2 193 202.30	0.25[34)]	548 300.58	2[14]	423 357.97
	Tomato (Stems and leaves)	7 570.00	551 732.30	0.30[34)]	165 519.69	2[14]	150 379.69
	Cabbages (Foliages)	2 288.20	130 616.10	2.30[33)]	326 540.25	2[14]	321 963.85
	Total	4 903 365.00	39 489 742.90		43 344 981.20		33 743 385.00

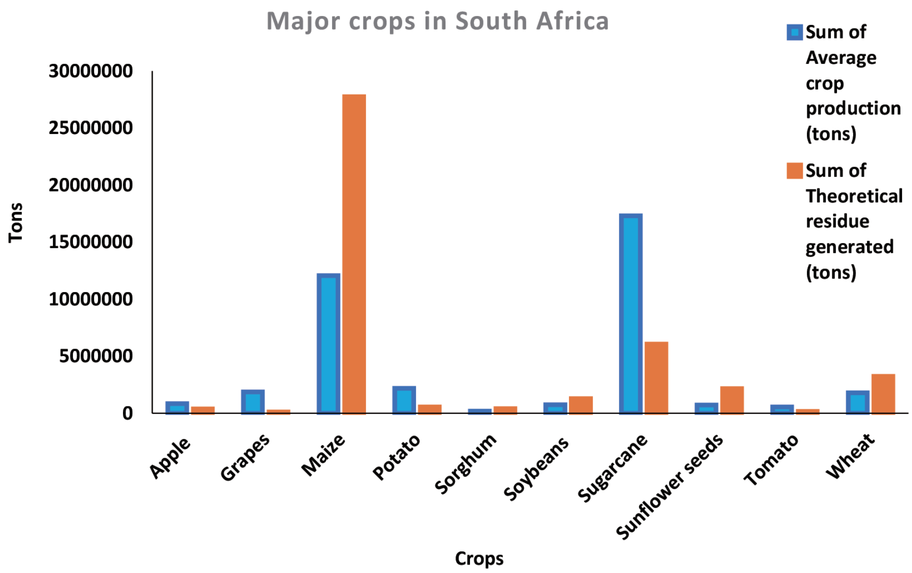

Fig. 9 Average production of major crops and their theoretical generated residues.

mental impact/implications of continuous sustainability involves all round climate change mitigation strategies/measures aimed at the environmental protection, waste management, waste to wealth technological approach and energy conservation and renewability. Drastic reduction in greenhouse emissions and pollution are among the clear goals of sustainable measures to endear biofuel production from Agriculture. There are other unintended negative impacts which may arise that may affect water, land, ecosystems, agricultural practices and so on. The processing of biofuels from agricultural feedstock and technologies highlighted in this study may also adversely have an environmental impact, in addition to the scale of production, land use, commercialisation and industrialisation. Bioenergy technology mix and introduction from biomass reduces or offsets carbon dioxide from the atmosphere therefore contributing in the trade-off of climate vs energy. Most of the feedstocks and their residues also generate co- and value-products for other attendant applications uses thereby conserving energy and limiting costs.

Looking at the wide range of feedstocks/residues in addition to the production and processing technologies in South Africa, there is a concomitant wide range of environmental impacts and outcomes. It has been noted in some research, that the impact of producing biofuels from first generation feedstocks resulted in reduction in emissions between 22–62 percent in comparison with the fossil fuel counterpart.

6 Conclusion

In conclusion, the present work assessed residues from 21 major different crops grown in SA which are grouped into: grains, oilseeds, deciduous fruits and vegetables. The study established that:

- An estimated 13.5 Mt of crop residues are potentially available in South Africa per annum to be harnessed for sustainable biofuel production.
- The data generated in the present study will serve as a basis for potential investor's decision in bio-refinery industry in South Africa.
- The 2050 renewable energy target is possible if the present data is combined with other renewable energy sectors such as solar, wind, hydrothermal etc., hence providing a win-win scenario for all stakeholders.
- It will also lessen the burden associated with the use of non-renewable sources of energy in South Africa. Biofuel industry based on crop residues has potential to create more jobs in agricultural sector especially in previously disadvantaged rural areas of South Africa thereby changing the rural habitant farmer's life style and economy.
- Information provided in this review will help the government in supporting the development and advancement of second-generation biofuels through Biofuel Task Team.
- The commercialization and initial pilot plant of lignocellulosic biofuel is still a challenge and needs government support in most cases especially subsidies and accelerating research and development as the industry is still young in international scene. The success of biofuel industry in South Africa depends on many factors such as good infrastructure, supply of reliable feedstock and efficient advanced biomass conversion technologies but most importantly, a well-established policy in order to attract potential investors in this industry.

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