

---

# Sugarcane Bagasse and Cellulose Polymer Composites

---

Teboho C. Mokhena, Mokgaotsa J. Mochane,  
Tshwafo E. Motaung, Linda Z. Liganiso,  
Oriel M. Thekisoie and Sandile P. Songca

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.71497>

---

## Abstract

Waste recycling has been the main topic of various scientific researches due to environmental management. Renewable agricultural sources such as pineapple leaf, sisal, jute, piassava, coir, and sugarcane bagasse are among agro waste, normally known as biomass, which is recently used for reinforcing polymeric materials. Sugarcane bagasse fiber residues has been extensively investigated and employed as a source of reinforcement of polymers. The major residue is normally burnt for energy supply in the sugar and alcohol industries and as a result, tons of ash is created. The ash contained inorganic components which are valuable for reinforcement in polymeric materials. This chapter reports on the use of sugarcane bagasse, sugarcane bagasse ash (SBA) and its cellulose as reinforcing fillers for polymers.

**Keywords:** sugarcane bagasse ash, reinforcement, energy production, cellulose, sugarcane bagasse

---

## 1. Introduction

In the past few years, the high utilization of fossil fuels has led to difficulty in recovering petroleum reserves, which has enhanced environmental concerns together with energy security drawbacks [1]. These issues together with global climate change due to greenhouse gas have led researchers to consider alternative fuels based on sustainable bio resources. Agro-energy crops and plant residues are promising low-cost, sustainable biomaterials for biofuel and power generation.

First generation bioethanol has been employed mostly for vehicle fuels which resulted in lowering carbon dioxide (CO<sub>2</sub>) in comparison to fossil fuels. On contrary, the high demand

for first generation ethanol requires high feedstock production which will lead to food against fuel concerns. The second-generation biofuels becomes the favorite choice since it depends on non-food bio resources such as lignocellulosic. The lignocellulosic materials are relatively inexpensive and available in large quantities. One of the most well-known lignocellulosic materials for second-generation ethanol production is sugarcane bagasse [1, 2].

According to the available literature about 640–660 Mton of sugarcane could generate a total of 28,500 million liters of alcohol, with the aim of producing 45.4% of sugar and 54.6% of alcohol. This would apparently produce 160 Mton of sugarcane bagasse [3]. Generally sugar cane bagasse consists of cellulose (41.0–55.0 wt%), hemicellulose (20.0–27.5 wt%), lignin (18.0–26.3 wt%) and others (~7.0 wt%) attributed to inorganic materials [3–5]. Sugarcane bagasse can be employed for other applications that include extraction of all the constituents (cellulose, hemicellulose and lignin) [4, 5]. Furthermore the sugarcane bagasse ash could be used as raw material for obtaining new type of mortars and concretes [6]. In fact, it has also a potential to partially replace Portland cement [7].

In this chapter we cover all the aspects related to the residues and/or left overs resulting from sugar extraction process. These residues can be used for various applications especially in polymer composite. The high mechanical strength of the sugar bagasse fibers as well as its constituents such as lignin, hemicellulose and cellulose can be added to polymeric matrices to produce multifunctional composite materials. The ashes from the burning of sugar bagasse as source of energy for sugar extraction and alcohol industry can also be used for polymer reinforcement.

## 2. The production of sugarcane bagasse globally (producing countries)

Sugarcane bagasse originates from Asia and can be found mostly in tropical and subtropical climates [1]. For instance, *Saccharum spontaneum* is endemic in the wild from eastern and northern Africa, through the Middle East, to India, China, Taiwan and Malaysia through the Pacific to the New Guinea. Globally (mostly in Latin America and Asia), the production of sugarcane bagasse was approximately 1900 million metric in the past 5 years. Brazil is by far the world's largest sugarcane producer with around 740 million ton cane crushed in the 2010/2011 harvest season, which is about 43% of the global production. **Table 1** summarizes the sugarcane crop production in selective countries between years 2009 and 2013. Brazil is also the largest exporter of ethanol, and it is widely expected that Brazil has a large potential for growth in the next decades. At the sugar mills, bagasse has been used to fuel the boilers that supply the thermal and electrical power needed for the internal processes of the sugar mills.

Columbia has been producing sugarcane and palm oil since the early 1900s. Most of Colombia sugarcane bagasse plantations are situated around the Cauca River Valley, and grow the whole with the potential to produce 950,000 Ld<sup>-1</sup> of ethanol from sugarcane juice. There are approximately more than 20,000 registered sugarcane growers regions in South Africa which include the province of KwaZulu-Natal, Mpumalanga and Eastern Cape. The majority of sugarcane

Country	Year	Average production (million metric ton yr <sup>-1</sup> )	Average annual yield of sugarcane (metric ton ha <sup>-1</sup> )
Brazil	2013	743.0	120.0
Mexico	2012	42.5–44.6	65.0
Colombia	2013	21.5	108.0
Argentina	2010	19.0	56.0
Cuba	2009	11.6	22.4
India	2012–2013	350.0	70.0
Thailand	2013	100.1	62.6
China	2013	125.5	–
South Africa	2013	20.3	–

**Table 1.** Sugarcane production from different countries between 2009 and 2013 [1, 8–10].

crop is grown in the highest latitude in the country which is in KwaZulu-Natal. India is one of the largest producers of sugar in the world and is the world’s second largest producer next to Brazil of sugarcane. Its cane is normally planted throughout 3 seasons in the northwest region of the country. Previously Cuba used to be one of the largest sugar exporters in the world until it was hit by commercial trade blockage 4 decades ago [1, 8–10].

### 3. Physio-chemical properties of sugar bagasse

#### 3.1. Fibers

Sugarcane bagasse is a fibrous material obtained as a residue from the sugarcane after crushing to extract the juice. Its stalk is composed of two components *viz.* outer rind and inner pith [11, 12]. The rind consists of strong fibrous structure protecting the inner soft spongy structured material (pith). It contained long finer fibers arranged randomly throughout the stem bound together by lignin and hemicellulose, while the inner component contains small fibers with major part being sucrose. Chemically, sugarcane bagasse composed of cellulose, hemicellulose and lignin [13]. The content of these constituents may vary depending on the growth region and conditions. About 40–50% of dried sugarcane bagasse is cellulose with 25–35% is hemicellulose and 17–20% lignin with some wax 0.8% and ash 2.3% [12, 13]. All these components have similar structure as the constituents of every natural lignocellulosic fibers and, the only difference is their content. In the next subsection only part of sugarcane bagasse and products that can be used as reinforcing fillers of various polymer matrices will be discussed. Moreover, carbonized sugar bagasse can be prepared by alkali treatment followed by burning in the furnace at higher temperature (>500°C) to produce ashes as shown in **Figure 1** [14]. These particles also serve as the most potential reinforcement for various polymeric materials. They appear solid in nature with irregular finer shapes; and it composed mainly of SiO<sub>2</sub>, AlO<sub>3</sub>, MgO, and Fe<sub>2</sub>O<sub>3</sub>.

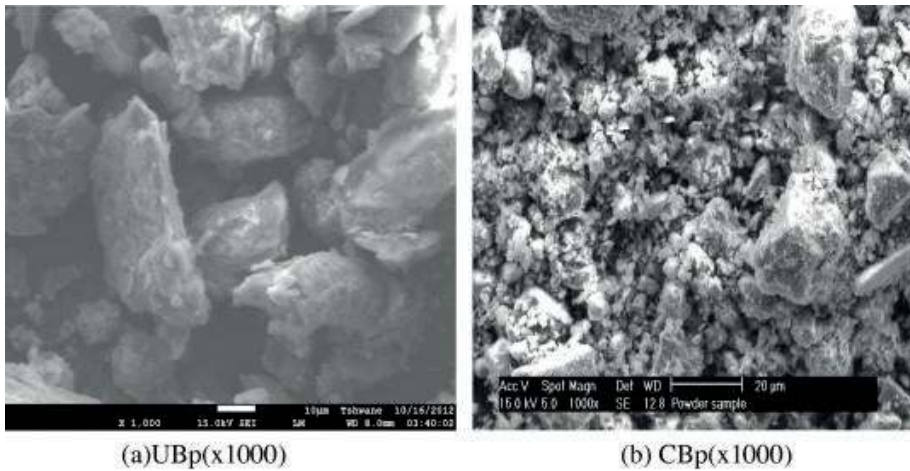


Figure 1. SEM images of (a) uncarbonized and (b) carbonized sugar bagasse [14].

### 3.1.1. Cellulose

Cellulose from sugarcane bagasse can be extracted by using either chemical or mechanical means [15–17]. In some cases both of these (chemical and mechanical) methods are used in order to control the size as well as to improve the purity of the resulting product. A combination of mechanical shearing (or sonication) and controlled acid hydrolysis (or combination of acids) are often used to isolate the cellulose. This kind of cellulose is also known in literature as microfibrillated cellulose (MFC) due to their size diameters ranging from few nanometer to few micrometers, while their length may be above a micron [15–18]. Depending on the time and acid concentration the lateral amorphous region of the MFC can be dissolved to obtain highly crystalline particles. This kind of cellulose particles are known in literature as cellulose nanocrystals (CNC), cellulose nanowhiskers (CNW), cellulose whiskers (CW), microcrystals, or cellulose nanoparticles. These particles have diameters ranges between 5 and 20 nm and the lengths from 20 nm to 1 micron. Tensile strength and/or modulus of these particles and the abundant availability of their source spurred much interest as replacement of engineered reinforcing fillers [19]. The presence of the hydroxyl groups on the surface of these particles offers the advantage for their functionalization [20, 21].

### 3.1.2. Ashes

Sugarcane industries produce large quantities of sugarcane bagasse (i.e., fibrous residue/left over after sugarcane stalks are crushed to extract their juice) annually which in turn is used in the plant for energy co-generation for sugar processing and/or alcohol production [22–26]. Consequently, the black solid waste produced is collected using a bag house filter as a by-product known as sugarcane bagasse ashes. The collected by-product often consists of fine burnt and coarse unburnt or partially burnt particles. These ashes are non-biodegradable which causes environmental concerns considering their disposal. Some industries adopted

the unfriendly disposal methods such as mixing the ash with water and discarding it into the open field and/or using these ashes as fertilizers. The ashes are composed of highly crystalline phases *viz.* quartz ( $\text{SiO}_2$ ), cristobalite ( $\text{SiO}_2$ ), potassium carbonate ( $\text{K}_2\text{CO}_3$ ), calcium phosphate ( $\text{Ca}_3(\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ ), hematite ( $\text{Fe}_2\text{O}_3$ ), and mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) [24]. The percentage of these constituents varies with crystalline silica being the major constituent (60 to above 80%). The variation is as a result of the growing conditions of the sugarcane bagasse as well as other factors such as soil type, fertilization methods, and soil management. Moreover, the physical and chemical compositions are directly influenced by combustion processes such as combustion temperature and time, cooling duration, ash collection methods and grinding conditions [27]. It is noteworthy mentioning that despite these variations and the reasons given from each study, it can be concluded that these variations comes due to the fact that sugar bagasse is a natural material. The chemical composition can vary as tabulated in **Table 2**. These properties plays major role on the performance of the product manufactured from these ashes. Therefore one of the prerequisite before implementing sugarcane bagasse ashes is to characterize their composition using techniques such as XRD (for crystallography) and EDX (for chemical analysis) as well as to measure their size and/morphology using microscopic techniques such as SEM and other. Loss on ignition (LOI) is also considered to measure the organic matter in the sample or the amount of carbon which reflects extends of ashes combustion. The higher LOI indicates that the amount of unburnt carbon in the ash. The crystalline phase of mullite depends on the ratio of Si/Al of the material. At low Al content the tetragonal structure is obtained which changes to orthorhombic structure at higher Al content. Its nucleation can be accelerated by adding additives, flux or mineralizer. The degree of crystallinity for silica is also dependent on the combustion temperature. If higher temperatures are used during combustion, the more crystalline silica is obtained and for low combustion temperatures the opposite prevails. These changes in combustion affect the specific area and the morphology of the resulting ashes. As mentioned earlier the carbon content can be controlled by these

$\text{SiO}_2$	60–86
$\text{Al}_2\text{O}_3$	1–14
$\text{Fe}_2\text{O}_3$	1–14
$\text{TiO}_2$	0.2–3
CaO	2–7
MgO	0.05–2
MnO	0.1–0.5
$\text{K}_2\text{O}$	0.2–6
$\text{P}_2\text{O}_5$	0.5–3.5
$\text{SO}_3$	0.2–2.5
$\text{Na}_2\text{O}$	0.01–0.1
$\text{Cr}_2\text{O}_3$	0.01–0.1

**Table 2.** Chemical composition of sugarcane bagasse ashes [24].

changes in the combustion temperatures as it can be obtained at burning temperatures ranging between 400 and 500°C.

## 4. Applications of composites

Biomass residues generated from agro-businesses gained much attention as reinforcement of various polymeric materials due to their inherited properties (i.e., biodegradability and renewability, etc.) and low-cost production. In addition, the consciousness about conservation of the environment has forced the industrial and scientific communities to look for an alternative for the agro-business generated waste. Several biomass residues (i.e., rice husks, maize stalks and sugarcane bagasse) were successfully incorporated into different polymers to improve their mechanical and physical properties. Herein we will discuss the application of sugarcane bagasse as reinforcing filler for various polymeric materials. Different forms of fillers can be generated/produced from sugarcane bagasse waste which include sugarcane bagasse ashes (SBA), fibers (SB), nanocrystals (CNCs), cellulose and micro/nanofibers (MFC or CNF) were incorporated in various polymer matrices such as polypropylene (PP) [28], low density polyethylene (LDPE) [29] polyethylene oxide (PEO) [30], nylon [31] as well as thermosets [32, 33].

### 4.1. Composites processing

It is recognized that the processing technique plays major role on the dispersion of the fillers in the polymer composite materials. There are three widely used methods which include melt compounding, *in situ* polymerization and solution casting. It is of interest to mention that the size of the filler also plays a significant role on the dispersion especially with regard to their processing technique. In most cases micro-fillers (fibers) are preferably prepared *via* melt compounding which is the most conducive method with regard to industrial scale-up process. On the other hand, the nanostructured sugar bagasse-based fillers (e.g., CNCs) are preferably prepared *via in situ* or solution casting which are known to improve their dispersion because these filler are mostly obtained in a solution form which controls their processability. This in turn have forced most of the fabrication methods to concentrate on keeping the dispersed state of the fillers in the solution by adopting either the solution processing technique or polymerization in the presence on the nanostructured fillers.

#### 4.1.1. Melt compounding

Melt compounding is the most preferable processing technique for industrial scale-up. This technique is usually suitable for highly hydrophobic polymers which normally lead to inhomogeneity of the resulting composite materials. The functionalization/chemical modification of the fillers and/or polymer can be applied to overcome the agglomeration in order to achieve durable and desired properties [14, 34]. The alkali pre-treatment of sugarcane bagasse is often applied to increase roughness of the fibers by removing some of the wax and non-cellulosic substances. It was reported that this kind of treatment was not suitable to improve the interaction/adhesion

and dispersion of the fibers for highly hydrophobic polymer matrices which causes detrimental effect on the properties of the resulting composite material [35].

Compression molding was also used to prepare the SB-based composites [36]. This method, however, resulted in blisters, weak interfacial adhesion and inhomogeneous fiber distribution, regardless of the fiber retreatment.

Melt extrusion followed by melt compression of SB/HDPE composites was studied by Mulinari et al. [37]. The SB cellulose was extracted using sulfuric acid in a reactor followed by surface modification using zirconium oxychloride ( $ZrOCl_2 \cdot 8H_2O$ ). In another studies, they used thermokinetic mixer followed by compression molding [17, 38]. The modification using  $ZrOCl_2 \cdot 8H_2O$  reduced the extent of agglomeration in the composite materials. Moreover, the adhesion between the cellulose and HDPE was improved by surface modification. It was concluded that these processing methods are applicable to produce composites materials using hydrophobic polymers such as HDPE and PP. It worth mentioning that these melt processing methods did not have a significant influence on the extent of the dispersion of the fillers as well as their adhesion. As far as the modification of the filler surface is concerned, it can be concluded that regardless of the type/structure (form) of filler the surface modification can improve the dispersion and adhesion for improved properties.

#### 4.1.2. *In situ processing*

The addition of the filler into the precursor (polymer monomer) increases the possibility of good dispersion and interaction between the polymer and filler. Motaung et al. [31] prepared CNC/nylon nanocomposites *via in situ* polymerization. The CNC were added into hexamethylenediamine (i.e., nylon monomer) followed by sonication to enhance the dispersion of the CNCs. Nevertheless, the content of the filler played a major role on the dispersion as well as adhesion. Despite the better dispersion obtained under this processing method, for CNC-based composites this scenario can cause a detrimental effect on the resulting properties of the composite materials. The interwhiskers network formed between the nanocrystals is important to achieve desired properties in CNC/polymer nanocomposites [39, 40].

#### 4.1.3. *Solution casting*

Sugarcane bagasse is currently used as a one of the sources of the cellulose nanocrystals (CNCs) for the reinforcing polymers. In these studies the state of dispersion of the CNC in water was maintained by adopting the solution casting method [41, 42]. In this method the nanocrystals are mixed with the polymers in a suitable solvent and allow the solvent to evaporate. Uniform distribution of the nanocrystals within the polymeric material was obtained which can lead to other physical and/or chemical properties. It is also essential to take into account the amount of the nanocrystals incorporated into the polymeric material since the higher the content may result in the agglomeration of the nanocrystals which could cause detrimental effect on the intended application or desired properties [42]. Similar preparation method was utilized in the preparation of SB fibers composites especially for polymers which are soluble in water [30].



#### 4.1.4. Other processing methods

Thermosets polymer composites are usually prepared by curing at a temperature depending on the resin-type. The casting of the constituent of the composites onto the steel mold followed by compression molding under certain conditions (pressure, time and/or temperature) influence the properties of the resulting composite material [43–45]. de Sousa et al. [43] studied the effect of pressure on the pre-treated chopped SB-polyester composites. They reported that the combination of all other parameters such as size of the filler, pre-treatment and pressure exerted during molding can be optimized to obtain the desired properties. It is interesting to note that the thermosets have an edge over other polymers due to the fact that it can offer high filler loadings (>65–80 wt%). In addition, the processing temperature is lower when compared to melt mixing and the easy processability. The disadvantage of these composites is that they are not recyclable, and the highly possible alternative is to use them as polymeric fillers or for heat generation. Nevertheless, there has been paradigm shift from synthetic polyesters to a new class of biodegradable resins to overcome the recycling issues [45].

## 5. Mechanical properties

There are several aspects that play a major role on the resulting mechanical properties of the composites materials such as adhesion, the size of the filler, the extent of dispersion. The adhesion and dispersion could also be dependent on the processing technique, the polarity and the surface modification applied on the fillers [14].

Slavutsky and Bertuzzi [41] prepared starch reinforced with sugar bagasse nanocrystals (CNCs) through solution casting. The strong interaction between starch and CNCs due to their chemical structure (polarity) similarity resulted in improved mechanical properties. This was promoted by hydrogen bonding resulting from hydroxyl groups on the surface of CNCs interacting with polymer chains which lead to an increase in Young's modulus (from 112 to 520 MPa) and tensile strength (from ~2.8 to ~17.4 MPa). The chemical treatment on either the CNCs or polymer matrix can also be used to improve the mechanical properties of the ensuing nanocomposites [42]. This is as a result of the crosslinking networks of the polymer which additional strength to the stiffer CNCs or the improvement of the interaction/adhesion between the polymer and the CNCs.

The modification of sugarcane bagasse cellulose with zirconium oxychloride was found to improve the interfacial interaction as well as dispersion which resulted in enhanced mechanical properties [17]. The composites were prepared by melt extrusion with high density polyethylene (HDPE) as polymeric matrix, and the Young's modulus and tensile strength increase respectively from 732 to 1233 MPa and 1.54 to 18.2 MPa. Such increment shows that the mechanical properties the high reinforcing effect of these SB-based fillers can be exploited if the suitable modification is applied. It was reported elsewhere that even the pre-treatment of the sugarcane bagasse fiber with strong acid followed by alkali can improve the interaction between the hydrophobic polymer (polypropylene in this case) and the inherently hydrophilic SB [38]. An increase of 16% in tensile strength and 51% in tensile modulus when compared to pure polymer was obtained.



Most of the SB polymer composites are prepared through melt compounding, thus is often based on the hydrophobic thermoplastics. This results in reduction of the mechanical properties of the resulting composite materials due to lack of adhesion as well as inhomogeneous fiber distribution [36, 37]. Chemical treatment can be utilized to improve the distribution as well as interaction/adhesion between highly hydrophilic SB fibers and hydrophobic thermoplastics [37]. Similarly, the sugarcane bagasse ashes (SBA)-based composites are prepared *via* melt mixing with an additional treatment being applied on either polymeric matrix or ashes to improve the mechanical properties [1, 46]. Since silica has been used as reinforcement of rubbers, the high content of silica in the SBA opens their applicability in rubber composites. Dos Santos et al. [47] reinforced natural rubber with SBA and found that the strong interfacial interaction between the SBA and rubber improved the mechanical properties. A recent study based on the comparison between the commercial silica and SBA reported that it is possible to replace the commercial silica with SBA as rubber reinforcing filler [48]. It was found that the replacement of commercial silica with SBA did not influence the mechanical properties of the composite materials that much.

The effect of NaOH treatment on the SB for the polyester composites was found to be improving the adhesion between the composites' components [45]. The alkali treatment led to finer fibers due to dissolution of the hemicellulose which increased the aspect ratio. A maximum improvement with only 1% NaOH was obtained with 13% in tensile strength, 14% in flexural strength and 13% in impact strength compared to untreated composites. This resulted in better interfacial adhesion between the polyester and NaOH-treated fibers. Other surface treatment of the SB fibers utilized as reinforcement of the thermosets were also studied to improve the interfacial adhesion between the fibers and the polymeric matrix [32, 49]. Despite the general observation of the mechanical properties which increases linearly with increase in fiber content some of these treatment significantly improves the overall performance of the thermosets composites [32, 49]. Vilay et al. [49] pre-treated the SB fibers with NaOH followed by acrylic acid (AA). They reported that the AA treatment improved the tensile strength, Young' modulus, flexural strength, and flexural modulus of the composites when compared to the untreated and NaOH-treated fibers. The elastic modulus was also increased for the treated fibers compared to other with glass transition ( $T_g$ ) shifting to higher temperatures. This could be due to the enhanced interfacial adhesion between the polymer and the filler as confirmed by increase in  $T_g$  justify the restriction of polymer chains movement by the reinforcing filler.

A rind and pith component of the SB-based unsaturated polyesters composites was investigated [50]. The flexural strength and flexural modulus were found to increase with fiber content for pith and rind fibers; and impact strength showed similar behavior. The tensile properties were also increased as compared to the unfilled polymeric material. It was, however, found that the rind outperform pith based composites. This was related to the structural difference between the pith and rind. The pith consists of big hollow cavities called lumen reducing bulk density of the fiber and acts as acoustic and thermal insulators. On the other hand, the rind have small size lumens and many finer cellulose fibers. Similar study was conducted elsewhere using poly (vinyl chloride) as matrix [11]. It was also reported that the rind/PVC displayed superior properties (i.e., flexural strength and modulus) when compared to the pith/PVC composites.

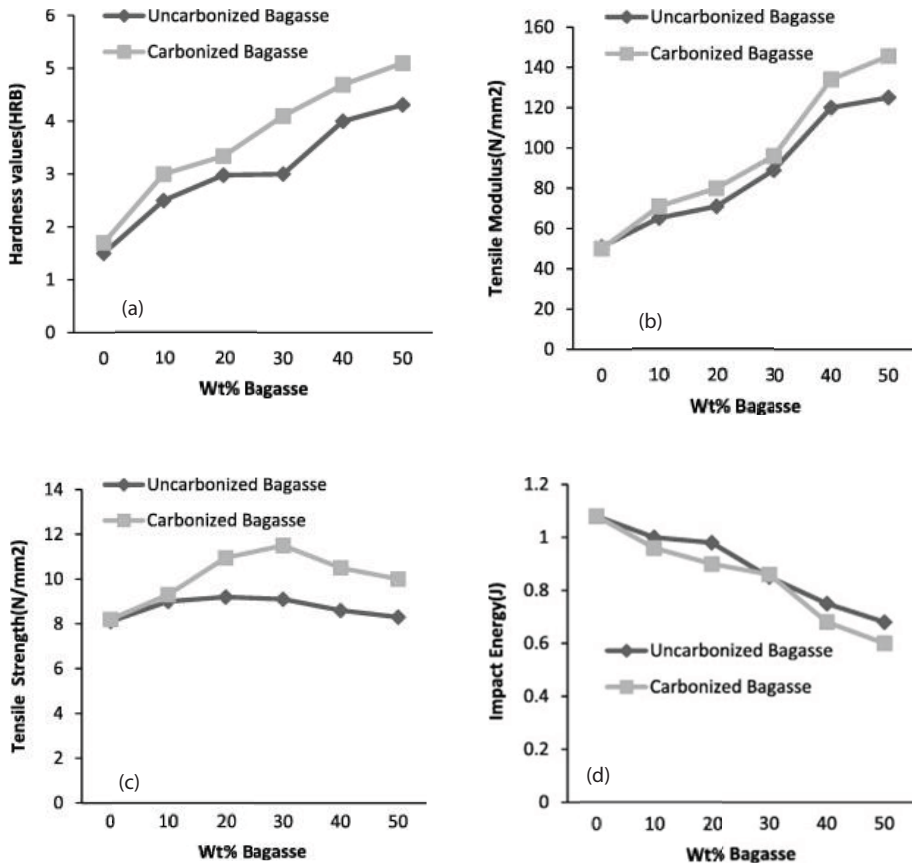


Figure 2. Variation of (a) hardness, (b) tensile modulus, (c) tensile strength, and (d) impact energy with wt% bagasse particles [14].

Agunsoye and Aigbodion [14] compared the mechanical properties of the uncarbonized and carbonized bagasse. The hardness was found to increase with an increase in fiber content due to the brittleness of bagasse particles; however the higher values for carbonized particles were associated with their larger surface area (Figure 2a). Similar observations were reported for tensile modulus due to the introduction of stiffer bagasse as compared to the polymeric matrix (Figure 2b). They observed an increase in tensile strength up to 30 wt% which was attributed to good distribution and dispersion resulting in strong interaction (Figure 2c). Above 30 wt%, the decrease was attributed to the physical interaction and immobilization of the polymer matrix by the presence of mechanical restraints. In addition, the decrease in interfacial area with an increase in particles content contributed to reducing the strength. On the other hand the impact strength results showed that the incorporation of these particles reduced the ability of the matrix to absorb energy and thereby reducing toughness. The ability to resist the

impact force was higher for uncarbonized bagasse as compared to carbonized bagasse which was related to the presence of high content of silica adding to the brittleness of the carbonized reinforced composites (**Figure 2d**).

## 6. Water absorption

Water absorption is the most important aspect considering the usage of the fiber polymer composite material in various applications with different environmental conditions. Natural fibers are hydrophilic which lead to their mechanical failure during an application. For example, for a sandwich fiber polymer composites delamination between fiber part and a polymer could ensue as a result of moisture absorption. This is directly dependent on the polymer-type, temperature, humidity, fiber loading, orientation, fiber-matrix adhesion, and permeability of the fibers [35, 50, 51]. On the other hand, surface modification of the fibers may improve the interfacial adhesion between the fibers and the polymer matrix which in turn enhance water absorption resistance. This apparently emanated from the hydrophobicity of the fillers and interaction with the hydroxyl groups on the surface of the fillers, thus decreasing the overall water absorption of the composites. Vilay et al. [49] reported that the treatment of the fibers with acrylic acid (AA) improves the water absorption resistance of the composites. The chemical treatment reportedly reduced the hydroxyl groups which improved adhesion between the fibers and polymeric matrix. The difference between the pith and rind on the water absorption was studied by Lee and Mariatti [50]. The bigger size of lumens in the pith-fibers facilitated the water absorption into the composite material when compared to the rind-based composites.

## 7. Thermal properties

There are two widely used techniques to study the thermal behavior of the natural fiber composites *viz.* thermogravimetric analysis (TGA) and differential scanning calorimeter (DSC). The TGA is usually used to evaluate both the thermal stability as well as the percentage of the fibers in the composites. The thermal stability of the SB-based fillers were studied by several authors to evaluate the effect of the extraction processes and surface modification [15, 16, 52]. The degradation steps of the fillers give an idea of the resulting product after extraction process. Similarly, the endotherms from DSC often shows the steps involves during heating process such as evaporation of water or moisture below 100°C.

Surface modification of the fibers can also change their thermal degradation behavior [32]. In the case of furfural as surface modification, it interacts mainly with lignin components (i.e., phenolic syringyl and guaiacyl) which alter the thermal degradation behavior of the fibers especially the step associated with lignin [32]. The alkali treatment improve the thermal stability of the fibers due to the removal of thermally unstable constituents of the fibers (i.e., hemicellulose, and wax). On the other hand the acid hydrolysis during the extraction of cellulose fibers (MFC) or cellulose nanocrystals (CNCs) introduces some thermally labile groups

on the surface of the fibers which results in reduction of thermal stability. In addition these harsh conditions may reduce the crystallinity and molecular weight of the cellulose which also contribute to the reduction of thermal stability.

## 8. Conclusions and remarks

The abundant availability of sugarcane bagasse offers an alternative toward the engineered fillers as well as the seasonal natural fibers as reinforcement of polymers for various applications. It can be argued that the hydrophilic character of sugar bagasse adversely affect the properties of the composite materials. Most of the studies based on surface modification of the fibers proved that these fibers can be applied in various fields such as aerospace, construction and automotive if the suitable surface modifier is applied. However, these modifications must be applied in such a way that they do not influence other properties especially for the fibers which are very sensitive toward harsh conditions which may adversely affect their durability and versatility. The inherited properties such as biodegradability and renewability has to be considered during the production of the composite materials. All processing techniques have their benefits and limitations. For example, the CNCs-based composites are preferably prepared *via* solution casting and *in situ* polymerization to obtain highly homogeneous distribution of the filler and interfacial adhesion without surface modification. In addition the low yield obtained from the extraction process *viz.* acid hydrolysis limit their application in melt compounding where large quantities of the filler are required.

## Author details

Teboho C. Mokhena<sup>1</sup>, Mokgaotsa J. Mochane<sup>1</sup>, Tshwafo E. Motaung<sup>1\*</sup>, Linda Z. Linganiso<sup>1</sup>, Oriël M. Thekisoë<sup>2</sup> and Sandile P. Songca<sup>1</sup>

\*Address all correspondence to: motaungt@unizulu.ac.za

<sup>1</sup> Department of Chemistry, University of Zululand, KwaDlangezwa, South Africa

<sup>2</sup> Unit for Environmental Sciences and Management, North-West University, Potchefstroom Campus, Potchefstroom, South Africa

## References

- [1] Bezerra TL, Ragauskas AJ. A review of sugarcane bagasse for second-generation bioethanol and biopower production. *Biofuels, Bioproducts and Biorefining*. 2016;**10**:634-647. DOI: 10.1002/bbb.1662
- [2] Loh Y, Suján D, Rahman ME, Das CA. Sugarcane bagasse—The future composite material: A literature review. *Resources, Conservation and Recycling*. 2013;**75**:14-22. Doi.org/10.1016/j.resconrec.2013.03.002

- [3] Teixeira SR, de Souza AE, Peña AFV, de Lima RG, Muguel AG. Use of charcoal and partially pyrolysed biomaterial in fly ash to produce briquettes: Sugarcane bagasse. *Alternative Fuel*. 2011;9. DOI: 10.5772/20505. ISBN 978-953-307-372-9. <http://creativecommons.org/licenses/by-nc-sa/3.0/>
- [4] Rahimi Kord Sofla M, Brown RJ, Tsuzuki T, Rainey TJ. A comparison of cellulose nanocrystals and cellulose nanofibres extracted from bagasse using acid and ball milling methods. *Advances in Natural Sciences: Nanoscience and Nanotechnology*. 2016;7
- [5] Pereira A, Martins GF, Antunes PA, Conrado R, Pasquini D, Job AE, Curvelo AAS, Ferreira M, Riul A Jr, Constantino JL. Lignin from sugar cane bagasse: Extraction, fabrication of nanostructured films, and application. *Langmuir*. 2007;23(12):6652-6659. DOI: 10.1021/la063582s
- [6] Romero M, Rincón JM, Teixeira S. Crystallization of a SiO<sub>2</sub>-CaO-Na<sub>2</sub>O glass from sugarcane bagasse ash. In: 1st Spanish National Conference. *Advances in Materials Recycling and Eco-Energy*; 2009
- [7] de Paula MO, Tinôco IFF, de Rodrigues S, da Silva CEN, de Souza CF. Potential of sugarcane bagasse ash as a partial replacement material for Portland cement. *Revista Brasileira de Engenharia Agrícola e Ambiental*. 2009;13(3):353-357. DOI: 10.1590/S1415-43662009000300019
- [8] Hofsetz K, Silva MA. Brazilian sugarcane bagasse: Energy and non-energy consumption. *Biomass and Bioenergy*. 2012;46:564-573. [Doi.org/10.1016/j.biombioe.2012.06.038](http://doi.org/10.1016/j.biombioe.2012.06.038)
- [9] García CA, Manzini F. Environmental and economic feasibility of sugarcane ethanol for the Mexican transport sector. *Solar Energy*. 2012;86(4):1063-1069. [Doi.org/10.1016/j.solener.2011.09.015](http://doi.org/10.1016/j.solener.2011.09.015)
- [10] Ferraro DO, Rivero DE, Ghersa GM. An analysis of the factors that influence sugarcane yield in Northern Argentina using classification and regression trees. *Field Crops Research*. 2009;112(2):149-157. [Doi.org/10.1016/j.fcr.2009.02.014](http://doi.org/10.1016/j.fcr.2009.02.014)
- [11] Wirawan R, Sapuan SM, Robiah Y, Khalina A. Flexural properties of sugarcane bagasse pith and rind reinforced poly (vinyl chloride). *IOP Conference Series: Materials Science and Engineering*. 2010;11:1-4. IOP Publishing. [iop.org/article/10.1088/1757-899X/11/1/012011/meta](http://iop.org/article/10.1088/1757-899X/11/1/012011/meta)
- [12] Motaung T, Anandjiwala R. Effect of alkali and acid treatment on thermal degradation kinetics of sugar cane bagasse. *Industrial Crops and Products*. 2015;74:472-477. [Doi.org/10.1016/j.indcrop.2015.05.062](http://doi.org/10.1016/j.indcrop.2015.05.062)
- [13] de Barros RdRO, de Sousa Paredes R, Endo T, da Silva Bon EP, Lee S-H. Association of wet disk milling and ozonolysis as pretreatment for enzymatic saccharification of sugarcane bagasse and straw. *Bioresource Technology*. 2013;136:288-294. [Doi.org/10.1016/j.biortech.2013.03.009](http://doi.org/10.1016/j.biortech.2013.03.009)
- [14] Agunsoye J, Aigbodion V. Bagasse filled recycled polyethylene bio-composites: Morphological and mechanical properties study. *Results in Physics*. 2013;3:187-194. [Doi.org/10.1016/j.rinp.2013.09.003](http://doi.org/10.1016/j.rinp.2013.09.003)

- [15] Sun JX, Sun XF, Zhao H, Sun RC. Isolation and characterization of cellulose from sugarcane bagasse. *Polymer Degradation and Stability*. 2004;**84**(2):331-339. Doi.org/10.1016/j.polymdegradstab.2004.02.008
- [16] Bhattacharya D, Germinario LT, Winter WT. Isolation, preparation and characterization of cellulose microfibrils obtained from bagasse. *Carbohydrate Polymers*. 2008;**73**(3):371-377. Doi.org/10.1016/j.carbpol.2007.12.005
- [17] Mulinari DR, Voorwald HJC, Cioffi MOH, da Silva CP, Luz SM. Preparation and properties of HDPE/sugarcane bagasse cellulose composites obtained for thermokinetic mixer. *Carbohydrate Polymers*. 2009;**75**(2):317-321. Doi.org/10.1016/j.carbpol.2008.07.028
- [18] Vasiljević J, Zorko M, Štular D, Tomšič B, Jerman I, Orel B, Medved J, Kovač J, Simončič B. Structural optimisation of a multifunctional water-and oil-repellent, antibacterial, and flame-retardant sol-gel coating on cellulose fibres. *Cellulose*. 2017;**24**(3):1511-1528. DOI: 10.1007/s10570-016-1187-4
- [19] Mariano M, El Kissi N, Dufresne A. Cellulose nanocrystals and related nanocomposites: Review of some properties and challenges. *Journal of Polymer Science Part B: Polymer Physics*. 2014;**52**(12):791-806. doi/10.1002/polb.23490
- [20] Montanari S, Roumani M, Heux L, Vignon MR. Topochemistry of carboxylated cellulose nanocrystals resulting from TEMPO-mediated oxidation. *Macromolecules*. 2005;**38**(5):1665-1671. doi/abs/10.1021/ma048396c
- [21] Saito T, Kimari S, Nishiyama Y, Isogai A. Cellulose nanofibers prepared by TEMPO-mediated oxidation of native cellulose. *Biomacromolecules*. 2007;**8**(8):485-491. doi/abs/10.1021/bm0703970
- [22] Faria K, Gurgel R, Holanda J. Recycling of sugarcane bagasse ash waste in the production of clay bricks. *Journal of Environmental Management*. 2012;**101**:7-12. Doi.org/10.1016/j.jenvman.2012.01.032
- [23] Schettino MAS, Holanda JNF. Characterization of sugarcane bagasse ash waste for its use in ceramic floor tile. *Procedia Materials Science*. 2015;**8**:190-196. Doi.org/10.1016/j.mspro.2015.04.063
- [24] Bahurudeen A, Kanraj D, Dev G, Santhanam M. Performance evaluation of sugarcane bagasse ash blended cement in concrete. *Cement and Concrete Composites*. 2015;**59**:77-88. Doi.org/10.1016/j.cemconcomp.2015.03.004
- [25] Sales A, Lima SA. Use of Brazilian sugarcane bagasse ash in concrete as sand replacement. *Waste Management*. 2010;**30**(6):1114-1122. Doi.org/10.1016/j.wasman.2010.01.026
- [26] Souza A, Teixeira SR, Santao GTA, Costa FB, Longo E. Reuse of sugarcane bagasse ash (SCBA) to produce ceramic materials. *Journal of Environmental Management*. 2011;**92**(10):2774-2780. Doi.org/10.1016/j.envman.2011.06.020
- [27] Katare VD, Madurwar MV. Experimental characterization of sugarcane biomass ash – A review. *Construction and Building Materials*. 2017;**152**:1-15. Doi.org/10.1016/j.conbuildmat.2017.06.142

- [28] Motaung TE, Liganiso LZ, John M, Anandijwala RD. The effect of silane treated sugar cane bagasse on mechanical, thermal and crystallization studies of recycled polypropylene. *Materials Sciences and Applications*. 2015;**6**(08):724. Doi.org/10.4236/msa.2015.68074
- [29] Motaung T, Mochane M, Makhetha T, Motloung S, Mokhothu T, Mokhena T, Moji R. Effect of mechanical treatment on morphology and thermal and mechanical properties of sugar cane bagasse–low-density polyethylene composites. *Polymer Composites*. 2015;**38**:1497-1503. doi/10.1002/pc.23717
- [30] Motaung TE, Mokhena TC. Effects of mechanical fibrillation on cellulose reinforced poly (ethylene oxide). *Materials Sciences and Applications*. 2015;**6**(08):713. Doi.org/10.4236/msa.2015.68073
- [31] Motaung TE, Mochane MJ, Liganiso ZL, et al. In situ Polymerization of Nylon-Cellulose Nano Composite. *Polym Sci*. 2017;**3**:1
- [32] Trindade WG, Hopareua W, Razera IAT, Ruggiero R, Frollini E, Castellan A. Phenolic thermoset matrix reinforced with sugar cane bagasse fibers: Attempt to develop a new fiber surface chemical modification involving formation of quinones followed by reaction with furfuryl alcohol. *Macromolecular Materials and Engineering*. 2004;**289**(8):728-736. doi/10.1002/mame.200300320
- [33] Trindade W, Hoareau W, Megiatto JD, Razera IAT, Castellan A, Frollin E. Thermoset phenolic matrices reinforced with unmodified and surface-grafted furfuryl alcohol sugar cane bagasse and curaua fibers: Properties of fibers and composites. *Biomacromolecules*. 2005;**6**(5):2485-2496. DOI: 10.1021/bm058006+
- [34] Vazquez A, Dominguez V, Kenny J. Bagasse fiber-polypropylene based composites. *Journal of Thermoplastic Composite Materials*. 1999;**12**(6):477-497. doi/abs/10.1177/089270579901200604
- [35] Boontima B, Noomhorm A, Puttanlek C, Uttapap D, Rungsardthong V. Mechanical properties of sugarcane bagasse fiber-reinforced soy based biocomposites. *Journal of Polymers and the Environment*. 2015;**23**(1):97-106. Doi.org/10.1007/s10924-014-0679-2
- [36] Luz S, Gonçalves A, Del'Arco A. Mechanical behavior and microstructural analysis of sugarcane bagasse fibers reinforced polypropylene composites. *Composites Part A: Applied Science and Manufacturing*. 2007;**38**(6):1455-1461. Doi.org/10.1016/j.compositesa.2007.01.014
- [37] Mulinari DR, Voorwald HJC, Cioffi MOH, da Silva MLCP, da Cruz TG, Saron C. Sugarcane bagasse cellulose/HDPE composites obtained by extrusion. *Composites Science and Technology*. 2009;**69**(2):214-219. Doi.org/10.1016/j.compscitech.2008.10.006
- [38] Cerqueira E, Baptista C, Mulinari D. Mechanical behaviour of polypropylene reinforced sugarcane bagasse fibers composites. *Procedia Engineering*. 2011;**10**:2046-2051. Doi.org/10.1016/j.proeng.2011.04.339
- [39] Favier V, Chanzy H, Cavaille J. Polymer nanocomposites reinforced by cellulose whiskers. *Macromolecules*. 1995;**28**(18):6365-6367. Doi/abs/10.1021/ma00122a053
- [40] Habibi Y, Lucia LA, Rojas OJ. Cellulose nanocrystals: Chemistry, self-assembly, and applications. *Chemical Reviews*. 2010;**110**(6):3479-3500. Doi/abs/10.1021/cr900339w



- [41] Slavutsky AM, Bertuzzi MA. Water barrier properties of starch films reinforced with cellulose nanocrystals obtained from sugarcane bagasse. *Carbohydrate Polymers*. 2014;**110**: 53-61. Doi.org/10.1016/j.carbpol.2014.03.049
- [42] Mandal A, Chakrabarty D. Studies on the mechanical, thermal, morphological and barrier properties of nanocomposites based on poly (vinyl alcohol) and nanocellulose from sugarcane bagasse. *Journal of Industrial and Engineering Chemistry*. 2014;**20**(2):462-473. Doi.org/10.1016/j.jiec.2013.05.003
- [43] De Sousa M, Monteiro S, d'Almeida J. Evaluation of pre-treatment, size and molding pressure on flexural mechanical behavior of chopped bagasse–polyester composites. *Polymer Testing*. 2004;**23**(3):253-258. Doi.org/10.1016/j.polymeresting.2003.09.002
- [44] Shibata S, Cao Y, Fukumoto I. Effect of bagasse fiber on the flexural properties of biodegradable composites. *Polymer Composites*. 2005;**26**(5):689-694. Doi/10.1002/pc.20140
- [45] Cao Y, Shibata S, Fukumoto. Mechanical properties of biodegradable composites reinforced with bagasse fibre before and after alkali treatments. *Composites Part A: Applied Science and Manufacturing*. 2006;**37**(3):423-429. Doi.org/10.1016/j.compositesa.2005.05.045
- [46] Teixeira JG, Gomes MG, Oliveira RR, Silva VA, Sartori MM, Ortiz AV, Moura EAB. Sugarcane bagasse ash reinforced HDPE composites: Effects of electron-beam radiation crosslinking on tensile and morphological properties. In: 2013 Interantional Nuclear Conference-INAC 2013
- [47] dos Santos RJ, Da Silva Agostini DL, Cabrera FC, dos Reis EAP, Ruiz MR, Budemberg ER, Teixeira SR, Job AE. Sugarcane bagasse ash: New filler to natural rubber composite. *Polímeros*. 2014;**24**(6):646-653. Doi.org/10.1590/0104-1428-1547
- [48] da Silva Ozorio M, dos Reis EAP, Teixeira SR, Belluci FS, Job AE. Sugarcane bagasse ash as a reinforcing filler in thermoplastic elastomers: Structural and mechanical characterizations. *Journal of Applied Polymer Science*. 2015;**132**(7):1-7 Doi/10.1002/app.41466
- [49] Vilay V, Mariata M, Taib RM, Todo M. Effect of fiber surface treatment and fiber loading on the properties of bagasse fiber–reinforced unsaturated polyester composites. *Composites Science and Technology*. 2008;**68**(3):631-638. Doi.org/10.1016/j.compscitech.2007.10.005
- [50] Lee S, Mariatti M. The effect of bagasse fibers obtained (from rind and pith component) on the properties of unsaturated polyester composites. *Materials Letters*. 2008;**62**(15):2253-2256. Doi.org/10.1016/j.matlet.2007.11.097
- [51] Mokhothu TH, John MJ. Review on hygroscopic aging of cellulose fibres and their biocomposites. *Carbohydrate Polymers*. 2015;**131**:337-354. Doi.org/10.1016/j.carbpol.2015.06.027
- [52] Mandal A, Chakrabarty D. Isolation of nanocellulose from waste sugarcane bagasse (SCB) and its characterization. *Carbohydrate Polymers*. 2011;**86**(3):1291-1299. Doi.org/10.1016/j.carbpol.2011.06.030