MATERIALS ENGINEERING | REVIEW ARTICLE

Sugarcane bagasse fiber reinforced composites: Recent advances and applications

Deepa G. Devadiga¹, K. Subrahmanya Bhat¹ and GT Mahesa²*

Abstract: Natural fiber composites expected to be in great demand in the coming years due to increased consumer awareness to reduce the waste and environmental pollution. Bagasse fibers available in plenty as an agro-residue and bio composites derived from such renewable resources offer potential for scale-up and value addition. This review provides an insight on current research trends on development and characterization of bagasse-based composites. Various chemical treatment methods and processing techniques used to improve the mechanical, thermal, acoustic, and aging properties of sugarcane bagasse reinforced composites are summarized in the review.

Subjects: Materials Science; Mechanical Engineering; Materials Science

Keywords: Sugarcane bagasse; polymer matrix; composites; mechanical properties; filler materials

1. Introduction

The use of agricultural crop residues for material development and fabrication offers various advantages such as easy and safe disposal at the end of service life, lightweight alternative materials with desirable acoustic properties, creation of pleasing environment and possible value addition to the agricultural products (Verma et al., 2015). Agricultural crops such as sugar cane, wheat, paddy, flax, banana, pineapple, etc., have been used by researchers to process them into materials with desirable properties. Such fibrous sources can be used as reinforcements in various forms such as woven mats, chopped fibers, and powders with polymers to form the polymer matrix composites (PMCs). Composites are basically made up of one or more discontinuous phase embedded in a continuous phase. Matrix acts as continuous phase and the phase which is stronger
and harder than continuous phase is termed as discontinuous phase, which is the reinforcement. Properties of constituent materials highly influence the properties of the composite material under consideration. The composite properties are approximated as the sum of volume fraction of the properties of the constituent materials. There are other factors that influence in the enhancement of the properties of the composite such as geometry, i.e., shape, size, and distribution of the reinforcement (Mahesha et al., 2019; Vidyashri et al., 2019; Yashas Gowda et al., 2018). The other factor that influence the properties of the composites is the alignment of the fibers, which results in the optimum tensile, flexural, and impact properties (Balasundar et al., 2019; Dinesh et al., 2020; Mahesha et al., 2017; Pickering & Le, 2016). Composite materials can be processed by various manufacturing techniques such as spraying, lay-up, resin transfer molding, compression molding, pressing, and stir casting. Lightweight materials with adequate specific mechanical properties are formed with such natural fiber-based raw materials as reinforcements (Thangaraju & Kannan, 2016; Vidyashri et al., 2019; Xiong, 2018). This review paper is based on the works carried out using sugarcane bagasse as filler with different binding materials to form composite materials. The effects of volume fraction of bagasse with different matrix systems, chemical modification methods applied and their effects on formed material properties are discussed under dedicated sections in the paper.

1.1. Sugarcane bagasse as fiber reinforcement

Sugarcane is grown worldwide as an agricultural crop, whose residue after extracting juice is regarded as bagasse. It is estimated more than 200 million tons of sugarcane bagasse obtained every year in India alone. Sugarcane is a renewable and natural agricultural resource (Almazan et al., 2001). Sugarcane bagasse approximately composed of 50% cellulose, 25% hemicellulose and 25% lignin (Huang et al., 2012). Ideal behavior shown by sugarcane bagasse as a composite reinforcement is due to the large content of cellulose present in this plant cellulose exhibits crystalline structure (Trindade et al., 2005). Chemically, bagasse contains about 50% α-cellulose, 30% pentosanes, and 2% ash. Composition in the fiber depends on age, source of fiber, soil condition, and extraction method followed. Details of the contents present in the bagasse is shown in Table 1.

Other sources of natural fibers such as rice straw, wheat straw has ash content 17.5% and 11.0%, respectively which is generally higher than that of sugarcane bagasse, due to which these are not frequently used as raw materials in forming the composites (Pandey et al., 2000). Bagasse is made up of rind and pitch. Rind, which is the outer hard part composed of fibers with low molecular weight contains cellulose, hemicellulose, and lignin (Almazan et al., 2001). Raw bagasse fibers are shown in Figure 1.

| Sl no | Composition of bagasse | References |
|-------|------------------------|------------|
| 1     | Cellulose 50.4%, Hemicellulose 28.5 %, lignin 14.9%, ash 2% | Xiong, 2018 |
| 2     | Cellulose 43%, Hemicellulose 10.1%, Lignin 33.23%, ash 1%, Moisture 6.45% | Ibrahim et al., 2020 |
| 3     | Cellulose 40%, Hemicellulose 24.5%, lignin 20%, wax 3.5%, ash 2.4%, silica 2% | Mulinari et al., 2009 |
| 4     | Cellulose 49.44%, hemicellulose 23.19%, Lignin 12.56%, Ash and extractives 14.8% | Ramleea et al., 2019 |
| 5     | Cellulose 36.32%, Hemicellulose 24.7%, lignin 18.14% | Vilay et al., 2008 |
| 6     | Cellulose 35.46%, Hemicellulose 31.25%, lignin 23.7%, ash 9.5% | Kordkheili et al., 2012 |
Cellulose content is about 40–50% of biomass which is a linear polymer made up of D-glucose units linked by β-1,4-glycosidic bonds with degree of polymerization up to 500–1500. Because of the extent of polymerization there exists inter- and intramolecular hydrogen bonds. Due to the orientation of bonds and secondary interactions cellulose has high tensile strength and is expectedly insoluble in most of the solvents (Jørgensen et al., 2007; Manzoor et al., 2012; Mooney et al., 1998). Cellulose may obstruct the degradation of products to its surrounding and diffusion of enzymes as a result of formation of denser layer of water because of the hydrophilic nature of cellulose (Mathews et al., 2006). Studies have shown bagasse has a density of 1.28 g/cc and crystallinity index of about 35% (Ibrahim et al., 2020). The reported tensile strength is in the range 20–50 MPa, tensile modulus as 2.7 GPa (Kordkheili et al., 2012). Sugarcane bagasse like all other natural cellulosic fibers have a natural disadvantage of hydrophilicity which tend to draw moisture from the surroundings resulting in swelling and loss of mechanical properties. To some extent, this deficiency of natural fibers could be minimized by modifying them by subjecting to various chemical treatments (Karp et al., 2013). Alkali, potassium permanganate, acetylation, silane treatment, benzoylation, acetone treatment, and acrylation are some of the commonly applied methods reported in literature. Such treatments aim to reduce or modify the available polar groups and to make them more hydrophobic to be compatible with polymeric matrix material to form the reliable composites (Aguir et al., 2010; Bilba & Arsène, 2008; Candido et al., 2012; La Mantia and Morealle, 2011; Lopez et al., 2012; Mahesha et al., 2018; Motaung et al., 2015; Timung 2015).

Table 2. Tensile properties of bagasse fibers

| Bagasse fibers | Tensile strength (MPa) | Tensile modulus (GPa) |
|----------------|------------------------|-----------------------|
| Untreated fibers (Ramleea et al., 2019; Vilay et al., 2008) | 20-50, 96 | 2.7, 6.42 |
| Alkali-treated fibers (Vilay et al., 2008) | 156 | 7.13 |
| Acrylic acid-treated fibers (Vilay et al., 2008) | 229 | 8 |
et al., 2016; Verma, 2012; Wirawan et al., 2011; Zhao et al., 2008). Table 2 shows tensile properties of raw and-treated bagasse fibers (Ramleea et al., 2019; Vilay et al., 2008).

1.2. Alkaline treatment
Alkali treatment or mercerization using sodium hydroxide is one of the commonly used treatment methods on raw fibers (Bam et al., 2019; Cao et al., 2006; Onesippe et al., 2010). This helps to remove lignin and wax content present in the outer portion of the fiber wall. Ionization of the hydroxyl group to the alkoxides take place which in-turn help in dissolution of low molecular weight components. But higher concentration of NaOH reported to have excess delignification of fibers resulting in the weakening of the fiber. Alkali treatment could also reduce the degree of polymerization, minimize lignin content and hemicellulose from the fiber. Some reports indicate alkaline treatment to influence on the number possible reaction sites on the fiber surface and an increase in the surface roughness, both contributing to the enhanced mechanical properties (Bam et al., 2019). The mechanical properties of biodegradable composites reinforced with bagasse fiber before and after alkali treatments is also reported (Cao et al., 2006). Bagasse fibers were immersed in 1, 3, 5% of NaOH solution at 25°C for 2 hours. Such fibers were rinsed with water for several times to ensure the removal of excess NaOH, and further neutralized with dilute acetic acid. For composite preparation fibers with polyesters resin were compression molded with a pressure of 10 MPa at 160°C for 10 min. Compared to 3 and 5% NaOH-treated fibers, 1% of NaOH-treated fiber reinforced composites showed significant improvement in flexural, tensile, and impact strengths (Cao et al., 2006). The effect of alkali pretreatment of fibers on thermal properties of sugarcane bagasse fiber reinforced cement composites is reported (Onesippe et al., 2010). The initial steps followed for fiber reconditioning was the heat treatment where the pyrolysis was carried out for 2 hours at 200°C under the controlled inert atmosphere. This was followed by chemical treatment with 5% Ca(OH)₂. The alkaline pre-treatment showed the reduction in lignin and hemicellulose while pyrolysis did not affect the general composition of fibers.

2. Silane treatment
Silylating reagents are used as coupling agent and reported to be effective in reduction of cellulosic hydroxyl groups at the fiber matrix interphase. Alkoxy group present can lead to the formation of silanols due to its hydrolysable property, which can further react with the hydroxyl groups present in the fiber surfaces leading to stable covalent bonds helping to reduce the hydrophilic nature of natural fibers. This treatment helps in better interfacial adhesion and increases strength of the natural fiber polymer composites (Bam et al., 2019).

2.1. Acetylation
Introducing acetyl group into cellulose fibers can be obtained by esterification method using acetylation reagents (Zhao et al., 2008). Reduction of the polar nature of natural fibers increases the dimensional stability of composites. The hydroxyl groups of the fiber (OH) reacts with acetyl groups (CH₃CO-) to make the surface more hydrophobic. The acetylation reduces the moisture absorption tendency of the fibers by about 50%. It is reported that hydroxyl groups present in the hemicellulose, lignin, and cellulose undergo acetylation (John & Ananddijwala, 2008). Studies on effect of acetylation on mechanical and thermal properties of sugarcane bagasse reinforced polypropylene composites were carried out. The fibers were initially treated with alkali followed by an acid before acetylation procedure was adopted. Polypropylene matrix was used for the composite preparation. Acetylation process increased the flexural strength and modulus but tend to decrease mechanical properties due to the chemical modification (Luz et al., 2008).

2.2. Permanganate treatment
In this method, permanganate group is responsible for the effective action in the treatment of the cellulosic fibers. This treatment is carried out by soaking different concentration of potassium permanganate for various time intervals after the alkali pre-treatment resulting in reduction of
hydrophilic nature of the fiber and improving the surface roughness thereby leading to an increased fiber-matrix interaction (Bam et al., 2019).

2.3. Peroxide and benzoylation treatment
Peroxide contains a specific functional group -ROOR, which can form a free radical RO that can react with the hydrogen group present in the matrix and cellulose fiber. Benzoyl group associated with benzyl chloride tends to reduce the hydrophilic nature of the treated fiber and tends to improve the interaction with the hydrophobic polymer matrix. Benzoylation of fibers shows better results when the fibers are pre-treated with alkali solution. This helps better fiber matrix linkage, increase in the strength of composites, reduction of water absorption, and improving its thermal stability (Bam et al., 2019).

3. Acetone treatment
Acetone treatment of cellulosic fibers creates a superior bonding with the matrix by dissolution of hemicellulose and other impurities thereby increasing the mechanical property of the materials. In a study, the raw bagasse fibers obtained after the extraction of the juice were cut into small sizes. About 20 gm of the bagasse fibers were then washed with acetone in the soxhlet apparatus for 1–1.5 hours. Considerable increase in flexural strength of treated bagasse fiber reinforced composites was observed when compared to untreated fiber-embedded composites (Acharya et al., 2009).

3.1. Mechanical characterization of bagasse-based polymer matrix composites
Several studies have been reported using bagasse as reinforcement in different polymer systems to form the composite materials. Table 3 gives some details with different combinations of polymer matrices with bagasse fibers. Bagasse fiber loading up to 30% with many synthetic and natural matrix systems were reported. The matrix systems such as polyvinyl alcohol, polyethylene, polypropylene, polyester, phenolic resin were reinforced with chopped bagasse fibers using vacuum bagging, Hand lay-up, and compression molding techniques. Bio-based matrix systems

| Table 3. Studies on mechanical characterization of bagasse reinforced composites |
|-------------------------------|-----------------------------|---------------------------------|------------------|
| **SI no.** | **Composites formed** | **Mechanical characterization** | **Ref.** |
| 1 | Polyvinyl alcohol with nano cellulose from bagasse | Tensile strength increased up to 5% (weight fraction) of nanocellulose and then decreased. | (Shenoy et al., 2019) |
| 2 | Corn starch matrix and fructose as plasticizer with corn husk fiber and sugar palm fiber (6% weight fraction) | Hybridization of corn starch and corn husk fibers with bagasse fibers improved the performance of bio composites | (Ibrahim et al., 2020) |
| 3 | Bagasse (20% weight fraction) with polypropylene | Increase in tensile strength by 15%, tensile modulus by 50%, flexural strength by 35%, flexural modulus by 32%, impact strength by 45% compared to neat resin specimens. | (Cerqueira et al., 2011) |
| 4 | Bagasse (20% volume fraction) with polypropylene | Tensile modulus enhanced by 60% and flexural modulus by 35%. | (Arrakhiz et al., 2013) |

(Continued)
### Table 3. (Continued)

| Sl no. | Composites formed                                                                 | Mechanical characterization                                                                                       | Ref.                        |
|--------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-----------------------------|
| 5      | Bagasse mats with polyethylene by vacuum bagging                                   | Tensile strength of untreated fibers was 96 MPa, 1% alkali-treated bagasse fibers = 156 MPa, acrylic acid-treated fibers = 229 MPa; tensile modulus of untreated fibers was 6.4 GPa, alkali-treated fibers = 7.13 GPa, acrylic acid fibers = 8 GPa. 20% volume fraction of untreated fibers increased elastic modulus by 52%; alkali-treated fibers increased by 61% in the composites. | (Vilay et al., 2008)        |
| 6      | Polyester-sugarcane bagasse continuous, aligned fibers with volume fraction 10, 20, and 30 % | Impact energy increase followed a linear trend with increase in fiber volume fraction.                             | (V. S. Candido et al., 2017) |
| 7      | Bagasse/wheat/eucalyptus used to form cement boards (FCBs)                          | Flexural behavior of FCB using bagasse fiber enhanced by 50% when 4% (weight fraction) of cement filled with bagasse fibers. | (Khorami & Ganjian, 2011)   |
| 8      | Bagasse-phenolic resins. Specimens were prepared with hand layup technique          | Sugarcane bagasse fibers help to reduce the water content and void in composites                                 | (Ramleea et al., 2019)      |
| 9      | Sugarcane bagasse (5% weight fraction)—polyester composites prepared by compression molding technique. | Modified bagasse fibers by esterification reinforced with polyester resulted in increase in tensile modulus by 71% compared to neat polymer specimens. | (Rodrigues et al., 2011)    |
| 10     | Bagasse (10, 15, 20 % volume fraction) untreated and alkali, acrylic acid-treated polyester composites prepared by vacuum bagging technique. | Higher tensile and flexural strengths obtained for acrylic acid-treated fiber reinforced composites with greater resistance to water diffusion. | (Vilay et al., 2008)        |
| 11     | Oil palm empty fruit bunch (OPEFB), sugarcane bagasse (SCB) with phenol formaldehyde (50% wt.%) using hand layup technique | Tensile strength of 50% bagasse reinforced composites offered 4.5 MPa, whereas 7:3 of OPEFB: SCB offered 5.5 MPa and modulus of 660 MPa. | (Kordkheili et al., 2012)    |
| 12     | Alkali-treated bagasse fibers were reinforced with polypropelene using twin screw extruding and injection molding technique. Fiber content were varied from 5 to 30% weight fraction | Tensile modulus of 25% fiber reinforced composites was 1460 MPa against 900 MPa of polymer alone. Flexural modulus of similar loaded composites was 1800 MPa, considerably higher than control specimens. | Kordkheili et al. (2012)    |
such as corn starch with fructose as plasticizer, starch, polylactic acid tried by researchers with bagasse fibers as reinforcement.

Fiber loading up to 20% in most of the studies resulted in improvement in mechanical properties such as tensile strength, elastic modulus, flexural modulus, flexural strength, and impact strength. Fiber treatment methods such as alkali treatment, acrylic acid, silane treatment have shown improvement in adhesion between the matrix systems and the bagasse fibers. Modification of fibers by chemical treatments has also resulted in improvement with respect to lesser water absorption tendencies by the composites.

Moroccan sugarcane bagasse biomass and low-density polyethylene (LDPE) composites were used to study the effect of fiber content on the mechanical properties (Moubarik et al., 2013). For fabrication of composites the LDPE in form of granules and dried bagasse cellulose with various weight percentages (10, 15, 20, and 25 wt.%) were extruded. Results showed an enhancement in mechanical properties with a gain of 72% in Young’s modulus at 25 wt.% fiber loading and a gain of 85% in flexural modulus at for similar fiber content. Bagasse filled recycled polyethylene bio-composites were produced by the compounding and compression molding (Agunsoye & Aigbodion, 2013). Two sets of composites were produced using uncarbonized (UBp) and carbonized (CBp) bagasse particles by varying its content from 10 to 50 wt.%. The tensile and bending strength of the composite specimens increased with increasing percentage of the bagasse to a maximum of 20 wt.% UBp and 30 wt.% CBp. The impact energy and fracture toughness decreased with change in wt.% of bagasse particles. These composites reported to have best properties up to 30 wt% particle additions. The process optimization studies showed carbonized bagasse particle addition above 30 wt.% to deteriorate material properties. The tribological behavior of recycled low-density polyethylene (RLDPE) polymer composites with bagasse ash particles exhibited higher wear resistance (Aigbodion et al., 2012). This behavior was mainly due to the presence of bagasse ash particles on the counter surface, which become a transfer layer and effect as a barrier. The wear rate proportionately increased with the applied load while it decreased with increasing volume fraction of the ash particles. The addition of ceramic content resulted in a drop in ductility accompanied with an increase in hardness which may further increase the wear resistance of the composites. Sliding speed and applied load are the parameters that has the highest physical as well as statistical influence on the wear property of composites.

Sugarcane fiber/polyester (SCRP) and glass fiber/polyester (GRP) composites were prepared using compression molding and hand-lay-up techniques (El-Tayeb, 2008). Results of friction and wear studies are significant as the composite properties can be as competitive to that of GRP composites. In the case of chopped sugarcane/polyester (C-SCR) composites, very smooth patches of polymer film due to plastic deformation shielded the surface of C-SCR composite pin specimens from damage which contributed to the higher wear resistance. Wear resistance of C-SCR composites reported to increase significantly with increasing load but decreased drastically for C-GRP composites. In addition, wear rate of C-SCR composites decreased by (20–50%) when the fiber length increased from 1 to 5 mm. With further increase in the fiber length to 10 mm, the wear rate increased drastically by 40–70%. Besides C-SCR composites gave friction coefficient of the same order as C-GRP composites (El-Tayeb, 2008). These results are useful for the standardization of composites for reliable preparation and evaluation of properties in-terms of fiber length and composition.

Bagasse fibers, like other plant fibers are basically multicellular where a bundle of individual cells is bound by natural polymers such as lignin and pectin. Hollow cavity exists in unit cell of bio fibers which decreases bulk density of fibers and acts as acoustic and thermal insulators. Treatments on fibers reduces void in fibers. Higher void in untreated fibers generates more pathways for water to start diffusing into composites (Vilay et al., 2008).

### 3.2. Application of bagasse ash as filler material

Studies on using bagasse ash as filler in composites have shown an improvement in mechanical properties with hybrid composites using different combinations of natural fibers as reinforcements.
Table 4. Applications of bagasse ash as filler in composites

| Sl no | Process used | Major observations | Reference |
|-------|--------------|--------------------|-----------|
| 1     | Hybrid bio composites of banana-flax, sisal-flax, banana-kenaf, sisal-kenaf were fabricated using bagasse ash of 350 nm as filler material (1, 3, 5% weight fraction) adapting the vacuum-assisted resin transfer molding. | Significant improvement in flexural, tensile and impact strength with hybrid banana-flax composites filled with 3% ash. Maximum flexural strength and tensile strength were observed for banana-kenaf hybrid composites filled with 5% of bagasse ash. Enhanced impact strength was observed for sisal-flax hybrid composites filled with 1% of bagasse ash. Highest thermal stability was for banana-kenaf composites filled with 3% ash. | (Vivek & Kanthavel, 2019) |
| 2     | Sugarcane bagasse ash as filler with varying presence of graphite in Al 7075 matrix with stir casting. | Maximum tensile strength of 299.4 MPa and BHN of 99.6 was recorded for 6% bagasse ash and 5% graphite in Al-7075 matrix. Percentage elongation was least (4.9%) for this combination compared to lower percentages of ash and graphite. | (Imran et al., 2016) |

Thermal stability has been observed for the composite materials with bagasse ash as filler material up to about 3% of filler content (Rossignolo et al., 2017). Some results observed with bagasse ash as filler are depicted in Table 4.

3.3. Ageing studies on bagasse composites

Feasibility of bagasse in different environmental conditions has been studied by researchers to use them or replace a part of the costly material by these fibers. Studies have shown that bagasse ash as binder in concrete gives adequate thermal stability to the concrete structures at elevated temperatures. Thermal aging of bagasse fibers with PLA resulted in enhancement in tensile properties up to first 4 weeks of ageing. Details of the aging-related studies reported is summarized in Table 5.

3.4. Applications of bagasse fiber composites

Because of low density, reasonable mechanical, acoustic, and thermal insulation properties, these fibers are being adapted for variety of applications in day-to-day life. Cement composites, particle boards, false ceilings, lightweight structures are some of the applications using bagasse as one of the reinforcement materials. Sugarcane bagasse, oil palm empty fruit bunch (25% each by weight) hybrid composites with phenol Formaldehyde (50% by weight) were used in the preparation of thermal insulation boards (Ramleea et al., 2019). Cement panels prepared using three levels of carbon nanotubes (CNT) (0.5, 1, and 1.5 weight %) were mixed with 10 and 20 weight % of bagasse fibers of 1.45 mm length using a rotary type mixer. Panels prepared thus found to possess flexural properties higher than neat cement panels. Composite panels contained 10% bagasse exhibited higher impact strength than 20% bagasse fiber embedded cement panels and neat cement specimens. It is worth noting that bagasse fiber composites could find applications in lightweight structures or articles with average to good properties where ability to bear the cost and engineering property requirements are moderate.
4. Conclusions
This review brings together the possible use of sugarcane bagasse as filler or reinforcement with different synthetic polymers and construction materials. The following conclusions are drawn from the published work as on date.

- Fiber loading up to 20% in most of the studies resulted in improvement in mechanical properties such as tensile strength, elastic modulus, flexural modulus, flexural strength, and impact strength.
- Fiber treatment methods such as alkali treatment, acrylic acid, silane treatment have shown improvement in adhesion between the matrix systems and the bagasse fibers.
- The limitations of manufacturing of such composites and property parameters if addressed properly, may result in environmental friendly materials.
- Bagasse ash as filler in composites results in improvement in mechanical properties with hybrid composites.
- Bagasse ash as binder in concrete gives adequate thermal stability to the concrete structures at elevated temperatures.

| Sl no. | Composites formed | Ageing study results | Reference |
|--------|-------------------|----------------------|-----------|
| 1      | Bagasse with polylactic acid subjected to thermal ageing | Tensile strength and elastic modulus both increased by 5.25% and 4.3% after 4 weeks of thermal ageing. Flexural modulus and flexural strength increased by 13.4 % and 5.16 % after 4 weeks of thermal ageing. | (Lila et al., 2019) |
| 2      | Sugarcane bagasse ash administered with Portland cement. | Residual compression and flexural strength of cubes formed were analyzed at room and elevated temperatures of 300, 400, and 500°C for 2 hours. Results shows that bagasse ash as binder in cement imparts resistance to concrete against elevated temperatures. The study concludes that bagasse ash can replace up to 15% of Portland cement. | (Gar et al., 2017) |
| 3      | 3:7 of Oil Palm Empty Fruit Bunch (OPEFB): Sugar Cane Bagasse (SCB) with Phenol Formaldehyde (50 % wt) | Least water absorption observed when compared to either of 50 % reinforcement by OPEFB or SCB alone at the end of 2 hours and 24 hours. | (Ramleea et al., 2019) |
| 4      | Bagasse, carbon nano tubes with Portland cement | Use of 20% CNTs with bagasse decreased water absorption and thickness swelling content of bagasse-cement composites. | (Kordkheili et al., 2012) |
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Author details
Deepa G. Devadiga
E-mail: deepagdevadiga121@gmail.com
K. Subrahmanya Bhat
ORCID ID: http://orcid.org/0000-0002-7948-8621
GT Mahesha
E-mail: mahesh.gt@manipal.edu
1 Department of Chemistry, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India.
2 Department of Aeronautical and Automobile Engg., Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India.

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References
Acharaya, S., Mishra, P. P., & Mehar, S. K. (2009). The influence of fibre treatment on the performance of bagasse fibre-reinforced polymer composite. Journal of Reinforced Plastics and Composites, 28(24), 3027–3036. https://doi.org/10.1177/0731684408094221
Aguiar, M. M., Ferreira, L. F., & Monteiro, R. T. (2010). Use of bagasse and sugarcane bagasse for the production of enzymes by lignocellulosic fungi. Brazilian Archives of Biology and Technology, 53(5), 1245–1254. https://doi.org/10.1590/S1516-89132010000500030
Agusnoye, J. O., & Agbodion, V. S. (2013). Bagasse filled recycled polyethylene bio-composites: Morphological and mechanical properties study. Results in Physics, 3, 187–194. https://doi.org/10.1016/j.rinp.2013.09.003
Agbodion, V. S., Hassan, S. B., & Agusnoye, J. O. (2012). Effect of bagasse ash reinforcement on dry sliding wear behaviour of polymer matrix composites. Materials & Design, 33, 322–327. https://doi.org/10.1016/j.matdes.2011.07.002
Almazan, O., Gonzalez, L., & Galvez, L. (2001). The sugar-cane, it’s byproducts and co-products. Sugarcane International, 3–8.
Arrakhiz, F. Z., Malha, M., Bouhfid, R., Benmoussa, K., & Gakis, A. (2013). Tensile, flexural and torsional properties of chemically treated alfalfa, coconut and bagasse reinforced polypropylene. Composites Part B: Engineering, 47(4), 35–41. https://doi.org/10.1016/j.compositesb.2012.10.046
Balasundar, P., Narayanasamy, P., Senthil, S., Dhabri, N. A. A., Prithvirajan, R., Shyam Kumar, R., Ramakumar, T., & Subrahmanya Bhat, K. (2013). Physico-chemical study of Pistacia (Pistacia vera) nut shell particles as a bio-filler for eco-friendly composites. Materials Research Express, 6(10), 105339.
Barn, S. A., Gundu, D. T., & Ong, F. A. (2019). The effect of chemical treatments on the mechanical and physical properties of bagasse fibre reinforced low density polyethylene composite. American Journal of Engineering Research, 8(4), 95–98. http://www.ajer.org/papers/Vol-8-issue-4/4K08049598.pdf
Bilba, K., & Arsène, M. (2008). Silane treatment of bagasse fibre for reinforcement of cementitous composites. Composites, Part A: Applied Science and Manufacturing, 39(9), 1488–1495. https://doi.org/10.1016/j.compositesa.2008.05.013
Candido, R. G., Godoy, G. G., & Gonsalves, A. R. (2012). Study of sugarcane bagasse pretreatment with sulfuric acid as a step of cellulose obtaining. International Journal of Nutrition and Food Engineering, 6(1), 6–10. https://doi.org/10.2821/zenodo.1082045
Candido, V. S., Da Silva, A. C. R., Simonsobis, N. T., Luz, F. S., & Monteiro, S. N. (2017). Toughness of polyester matrix composites reinforced with sugarcane bagasse fibers evaluated by Charpy impact tests. Journal Of Materials Research & Technology, 6(4), 334–338. https://doi.org/10.1016/j.jmrt.2017.06.001
Cao, Y., Shibata, S., & Fukushima, J. (2006). Mechanical properties of biodegradable composites reinforced with bagasse fibre before and after alkali treatments. Composites, Part A: Applied Science and Manufacturing, 37(3), 423–429. https://doi.org/10.1016/j.compositesa.2005.05.043
Cerqueiro, E. F., Baptista, C. A. R. P., & Muliniari, D. R. (2011). Mechanical behaviour of polypropylene reinforced sugarcane bagasse fibers composites. Procedia Engineering, 10, 2046–2051. https://doi.org/10.1016/j.proeng.2011.04.339
Dinesh, S., Kumaran, P., Mohanmurugan, S., Vijay, R., Singaravula, M. R., Vinod, A., Sanjay, M. R., Singhin, S., & Bhat, K. S. (2010). Influence of wood dust fillers on the mechanical, thermal, water absorption and biodegradation characteristics of jute fiber epoxy composites. Journal of Polymer Research, 27(1), 9 (13 pages). https://doi.org/10.1007/s10965-019-1975-2
El-Tayeb, N. M. (2008). A study on the potential of sugarcane fibers/polyester composite for tribological applications. Wear, 265(1–2), 223–235. https://doi.org/10.1016/j.wear.2007.10.006
Gar, P. S., Suresh, N., & Bindigandanivle, V. (2017). Sugar cane bagasse ash as a pozzolanic admixture in concrete for resistance to sustained elevated temperatures. Construction and Building Materials, 153, 929–936. https://doi.org/10.1016/j.conbuildmat.2017.07.107
Huang, Z., Wang, N., Zhang, Y., Hu, H., & Luo, Y. (2012). Effect of mechanical activation pretreatment on the properties of sugarcane bagasse/poly (vinyl chloride) composite. Composites, Part A: Applied Science and Manufacturing, 43(1), 114–120. https://doi.org/10.1016/j.compositesa.2011.09.025
Ibrahim, M. I. J., Sapuan, S. M., Zainudin, E. S., & Zuhri, M. Y. M. (2020). Preparation and characterization of cornhusk/sugar palm fiber reinforced Cornstarch-based hybrid composites. Journal of Materials Research & Technology, 9(1), 200–211. https://doi.org/10.1016/j.jmrt.2019.10.045
Imran, M., Khan, A. R. A., Megeri, S., & Sadik, S. (2016). Study of hardness and tensile strength of Aluminium-7075 percentage varying reinforced with graphite and bagasse-ash composites. Resource-Efficient Technologies, 2(2), 81–88. https://doi.org/10.1016/j.retiff.2016.06.007
John, M. J., & Anandidwala, R. D. (2008). Recent developments in chemical modification and characterisation of natural fibre reinforced composite. Polymer Composite, 29(2), 187–207. https://doi.org/10.1002/pmc.20461
Jorgensen, H., Kristensen, J. B., & Felby, C. (2007). Enzymatic conversion of lignocellulose into fermentable sugars: Challenges and opportunities. Biofuels, Bioproducts and Biorefining, 1(2), 119–134. https://doi.org/10.1002/bbb.6
Karp, S. G., Woiciechowski, A. L., Soccol, V. T., & Soccol, C. R. (2013). Pretreatment Strategies for delignification of Sugarcane bagasse: A review. Brazilian Archives of Biology and Technology, 56(4), 679–689. https://doi.org/10.1590/S1516-89132013000400019
Khorami, M., & Ganjani, E. (2011). Comparing flexural behaviour of fibre-cement composites reinforced bagasse: Wheat and eucalyptus. Construction and Building Materials, 25(9), 3661–3667. https://doi.org/10.1016/j.conbuildmat.2011.03.052

Kordkheili, H. Y., Hiziroglu, S., & Farsi, M. (2012). Some of the physical and mechanical properties of cement composites manufactured from carbon nanotubes and bagasse fiber. Materials & Design, 33, 395–398. https://doi.org/10.1016/j.matdes.2011.04.027

La Mantia, F. P., & Morello, M. (2011). Green composites: A brief review. Composites Part A: Applied Science and Manufacturing, 42(6), 579–588. https://doi.org/10.1016/j.compositesa.2011.01.017

Lila, M. K., Shukla, K., Komal, U. K., & Singh, I. (2019). Accelerated thermal ageing behaviour of bagasse fibers reinforced Poly (Lactic Acid) based biocomposites. Composites Part B 156, 121–127. https://doi.org/10.1016/j.compositesb.2018.08.068

Lopez, R., Poblan, V. M., Licea-Clavere, A., Avalos, M., Alvarez-Castillo, A., & Castano, V. M. (2012). Alkaline surface modification of sugarcane bagasse. Advanced Composite Materials, 21(2), 99–108. https://doi.org/10.1163/156856251X138020

Luz, S., Del Tio, J., Rocha, G., & Goncalve, A. (2008). Cellulose and cellulignin from sugarcane bagasse reinforced polypropylene composites: Effect of acetolysis on mechanical and thermal properties. Composites, Part A: Applied Science and Manufacturing, 39(9), 1362–1369. https://doi.org/10.1016/j.compositesa.2008.04.014

Mahesa, G. T., Shenoy, B. S., Kini, M. V., & Padmaraj, N. H. (2018). Effect of fiber treatments on mechanical properties of Grewia serrulata bast fiber reinforced polyester composites. Materials Today Proceedings, 5 (1), 138–144. https://doi.org/10.1016/j.matpr.2017.11.064

Mahesa, G. T., Shenoy, B. S., Vijaya Kini, M., & Subrahmanyam Bhat, K. (2017). Mechanical characterization and water ageing behavior studies of Grewia serrulata bast fiber reinforced thermoset composites. Journal of Natural Fibres, 14(6), 788–800.

Mahesa, G. T., Subrahmanyam Bhat, K., & Padmaraj, N. H. (2019). Biodegradable natural fiber reinforced polymer matrix composites: Technical updates. AIP Conference Proceedings, 2166, 020001. https://doi.org/10.1063/1.5131588

Monzoor, A., Khokhar, Z., Hussai, A., Monzoor, A., Uzma, A., Sh., A., Syed, Q., & Biaig, S. (2012). Dilute sulphuric acid: A cheap acid for optimization for bagasse treatment. Science International (Lahore), 41–45.

Mathews, J. F., Skopec, C. E., Nason, P. E., Zuccato, P., Torjat, R. W., Sugiyama, J., Himmel, M. E., & Bioczyk, J. W. (2006). Computer simulation studies of microcrystalline cellulose, Carbohydrate Research. Carbohydrate Research, 341(1), 138–152. https://doi.org/10.1016/j.carres.2005.09.028

Mooney, C. A., Mansfield, S. D., Touhy, M. G., & Saddler, J. N. (1998). The effect of initial pore volume and lignin content on the enzymatic hydrolysis of softwoods. Bioresource Technology, 64(2), 113–119. https://doi.org/10.1016/S0960-8524(97)00181-8

Motaung, T., Linganiso, L., John, M., & Anandjiwala, R. (2015). The effect of silane treated sugar cane bagasse on mechanical, thermal and crystallization studies of recycled polypropylene. Materials Sciences and Applications, 6(8), 724–733. https://doi.org/10.4236/msa.2015.68074

Moubairak, A., Grimi, N., & Boussetta, N. (2013). Structural and thermal characterization of Moroccan sugar cane bagasse cellulose fibers and their applications as a reinforcing agent in low density polyethylene. Composites Part B: Engineering, 52, 233–238. https://doi.org/10.1016/j.compositesb.2013.04.040

Munirani, R., Voorwald, H. J. C., Cioffi, M. O. H., Da Silva, M. L. C. P., Da Cruz, T. G., & Saron, C. (2009). Sugarcane bagasse cellulose/HDPE composites obtained by extrusion. Composites Science and Technology, 69(2), 214–219. https://doi.org/10.1016/j.compscitech.2008.10.006

Onesippe, C., Passe-Coutin, N., Toro, F., Delvasto, S., Bilbo, K., & Arsene, M. (2010). Sugarcane bagasse fibers reinforced cement composites: Thermal considerations. Composites, Part A: Applied Science and Manufacturing, 41(4), 549–556. https://doi.org/10.1016/j.compositesa.2010.01.002

Pandey, A., Soccol, C. R., Nigam, P., & Soccol, V. T. (2000). Biotechnological potential of agro-industrial residues: I. Sugarcane bagasse. Bioresource Technology, 74(1), 69–80. https://doi.org/10.1016/S0960-8524(99)00142-X

Pickingler, K. L., & Le, T. M. (2016). A review of recent developments in natural fibre composite and their mechanical performance. Composite Part A: Applied Science and Manufacturing, 83, 98–112. https://doi.org/10.1016/j.compositesa.2015.08.038

Rammeeo, N. A., Jawaid, M., Zainudin, E. S., & Yamani, S. A. K. (2013). Tensile, physical and morphological properties of oil palm empty fruit bunch/sugarcane bagasse fibre reinforced phenolic hybrid composites. Journal of Materials Research and Technology, 2(4), 3466–3474. https://doi.org/10.1016/j.jmrt.2019.06.016

Rodrigues, E. F., Maia, T. F., & Munirani, D. R. (2011). Tensile strength of polyester resin reinforced sugarcane bagasse fibres modified by esterification. Procedia Engineering, 10, 2348–2352. https://doi.org/10.1016/j.proeng.2011.04.387

Rossignolo, J. A., Rodrigues, M. S., Santos, S. F., & Junior, H. S. (2017). Improved interfacial transition zone between aggregate-cementitious matrix by addition sugarcane industrial ash. Cement and Concrete Composites, 80, 157–167. https://doi.org/10.1016/j.cemconcomp.2017.03.011

Shenoy, B. S., Mahesa, G. T., Kini, M. V., & Padmaraj, N. H. (2019). Effect of chemical treatments on hardness and toughness properties of grewia serrulata reinforced polymer composites. Journal of Mechanical Engineering Research and Developments, 42(6), 228–230. https://doi.org/10.26840/jmerd.04.2019.188.190

Thangaraju, R., & Kannan, G. (2016). Evaluation of mechanical characteristics of treated and untreated sugarcane fiber composites. Journal of Chemical and Pharmaceutical Sciences, 9(3), 652–656.

Timung, R., Deshvat, N. N., Goud, V. V., & Dasu, V. V. (2016). Effect of subsequent dilute acid and enzymatic hydrolysis on reducing sugar production from sugarcane bagasse and spent citrusenella biomass. Journal of Energy, 2016, 1–12. https://doi.org/10.1155/2016/8506214

Trindade, W. G., Hoareau, W., Megiatto, J. D., Raza, I. A. T., Castellon, A., & Frollini, E. (2005). Thermoset phenolic matrices reinforced with unmodified and surface-grafted furfuryl alcohol sugarcane bagasse and curaua fibres: Properties of fibres and composites. Biomacromolecules, 6(5), 2085–2496. https://doi.org/10.1021/bm0508006

Verma, D. (2012). Bagasse fibre Composite-A Review. Journal of Materials and Environmental Science, 3(6), 1079–1092.
Verma, D., Gope, P. C., Singh, I., & Jain, S. (2015). Composites from Bagasse fibers, Its characterization and applications. In K. R. Hakeem, et al. (Ed.), Agricultural biomass based potential materials (pp. 91–119). Springer.

Vidyashri, V., Lewis, H., Narayanassamy, P., Mahesha, G. T., & Bhat, K. S. (2019). Preparation of chemically treated sugarcane bagasse fiber reinforced epoxy composites and their characterization. Cogent Engineering, 6(1), 1708644. https://doi.org/10.1080/23311916.2018.1708644

Vilay, Y., Moratti, M., Mat Taib, R., & Todo, M. (2008). Effect of fiber surface treatment and fiber loading on the properties of bagasse fiber-reinforced unsaturated polyester composites. Composites Science and Technology, 68(3-4), 631–638. https://doi.org/10.1016/j.compscitech.2007.10.005

Vivek, S., & Kanthavel, K. (2019). Effect of bagasse ash filled epoxy composites reinforced with hybrid plant fibres for mechanical and thermal properties.

Wirawan, R., Sapuan, S. M., Yunus, R., & Abdan, K. (2011). Properties of sugarcane bagasse poly (vinyl chloride) composites after various treatment. Journal of Composite Materials, 45(16), 1667–1674.

Xiong, W. (2018). Bagasse composites: A review of material preparation, attributes, and affecting factors. Journal of Thermoplastic Composite Materials, 31(8), 1112–1146. https://doi.org/10.1177/0892705717734596

Yashas Gowda, T. G., Sanjay, M. R., Subrahmanya Bhat, K., Madhu, P., Senthamaraikannan, P., & Yogesh, B. (2018). Polymer matrix-natural fiber composites: An overview. Cogent Engineering, 5(1), 1446667. https://doi.org/10.1080/23311916.2018.1446667

Zhao, X., Wong, L., & Liu, D. (2009). Peracetic acid pretreatment of sugarcane bagasse for enzymatic hydrolysis: A continued work. Journal of Chemical Technology and Biotechnology, 83(6), 950-956. https://doi.org/10.1002/jctb.1889