



# Investigation of strength, durability, and water resistance of sorghum stalk particles reinforced with *Acacia caesia* fiber composites

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## Abstract

This study seeks to develop and assess a new hybrid natural composite reinforced with sorghum stalk particles (SSp) and *Acacia caesia* fibers (ACF) by examining its mechanical and physical properties, alongside microstructural analysis. The composite specimens were fabricated using the hand lay-up technique to ensure effective integration of the reinforcements within the matrix. Adding 12 wt% SSp to the test samples decreased their density by 40%, and as the fiber content grew, so did its water absorption (WA). Highest tensile strength (29.42 MPa) and modulus (3.83 GPa) were observed in the sample with 4 wt% and 12 wt% of SSp, respectively. At 12 wt% SSp, the maximum flexural strength and modulus were reached, while the highest impact strength of 106.14 J/m was observed at 8 wt% SSp. The addition of AC (18 wt%) fiber reinforcement to the SSp reinforced composite resulted in an improvement. The findings indicate that the incorporation of SSp and ACF enhances composite performance, with a reduction in density and an increase in water absorption at higher fiber content. Mechanical properties showed overall improvement, with tensile strength reaching its peak at lower reinforcement levels, flexural properties at higher content, and impact strength at intermediate levels. The developed composite demonstrates significant potential as a lightweight, cost-effective, and sustainable material for engineering applications.

**Keywords** *Acacia caesia* fiber · Hybrid composite · Mechanical properties · Sorghum stalk · SEM Analysis

## 1 Introduction

The world's demand for synthetic materials reached higher due to the exponential growth in the use of polymer materials for an extensive range of industrial sectors. Because of their inert nature, the polymers are major polluters of the environment [1]. Constant exposure to cyclic weathering conditions causes to produce toxic gases and particles, which in turn

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Extended author information available on the last page of the article

cause health problems in living things. Consumption of these materials is quickly increasing and having a devastating effect on the environment, despite ongoing attempts to recycle and regulate them [2]. The vast majority of these synthetic wastes wind up poisoning our water, land and debris into the oceans supplies; annually. Hence critical control the use of synthetics and find environmentally preferable substitutes [3, 4]. There are a number of industrial uses for synthetic materials, including in the construction, automotive, aerospace, and packaging industries; however, natural composites show great promise as a possible replacement [5]. Materials derived from plants, animals, and minerals are used to enhance natural composites. Natural plant fibers are widely used in various industries because to their biodegradability, affordability, and accessibility. Natural fiber-reinforced composites have attracted considerable interest because of their low density and advantageous mechanical characteristics [6–8]. Hybrid composites, made from two or more types of natural fibers, have recently become popular as a means of enhancing composite functionality. Moreover, it has been shown in a plethora of research that adding several fibers to composites improves their mechanical properties. Recent research has highlighted the benefits of hybrid composites, which improve overall performance by integrating various types of reinforcements [9, 10]. Furthermore, reinforcements derived from agricultural waste have been extensively investigated as economical and sustainable options in the development of composites [11]. Research on acacia fibers showed better tensile and flexural strengths related to composites made with single fibers [12]. The hybridized epoxy composite that included ACF outperformed the other composite samples in terms of impact energy, modulus of rupture, and shear strength. Hybrid polypropylene composites reinforced with coir fibers showed enhanced flexural modulus, impact strength, and flame resistance when filled with bark from ACF [13]. Adding ACF with filler epoxy composite increased its impact strength and tensile modulus. The ACF composite showed improved tensile and flexural with the inclusion of particles [14]. The test samples also showed an improvement in their resistance to moisture. Superior impact resistance to that of individual fiber reinforced composites was demonstrated by a hybrid sorghum and bagasse [15]. Adding clay to the *Holoptelea integrifolia/Ziziphus jujuba* seed particles hybrid polyester composite enhanced its tensile and flexural [16]. Reinforcing sisal fibers increases the flexural and tensile strength of polyester resin. made a hybrid epoxy composite with African teff and snake grass fibers as a substitute for gypsum boards; these materials are both economical and environmentally benign [17]. Sorghum seeds composites reinforced with coconut and palm shells exhibit much enhanced mechanical characteristics [18]. The enhancement in mechanical properties aligns with earlier research, which found that combining natural fibers with particulates improves load transfer and structural performance [19, 20]. The enhancement in mechanical properties aligns with earlier research, which found that combining natural fibers with particulates improves load transfer and structural performance [21]. Hybridization with Sorghum Stalk fillers also improved the tribological characteristics of epoxy composites supplemented with ACF. Composites made from agricultural byproduct sorghum stalk are being investigated in this research. In addition, the mechanical characteristics of the final composite are enhanced by combining them with a hitherto unstudied ACF, which demonstrated promising reinforcing capabilities in earlier research. This study aims to examine the potential benefits of cladding panels made from a combination of Sorghum stalk particles and a new type of ACF for use in insulating residential buildings.

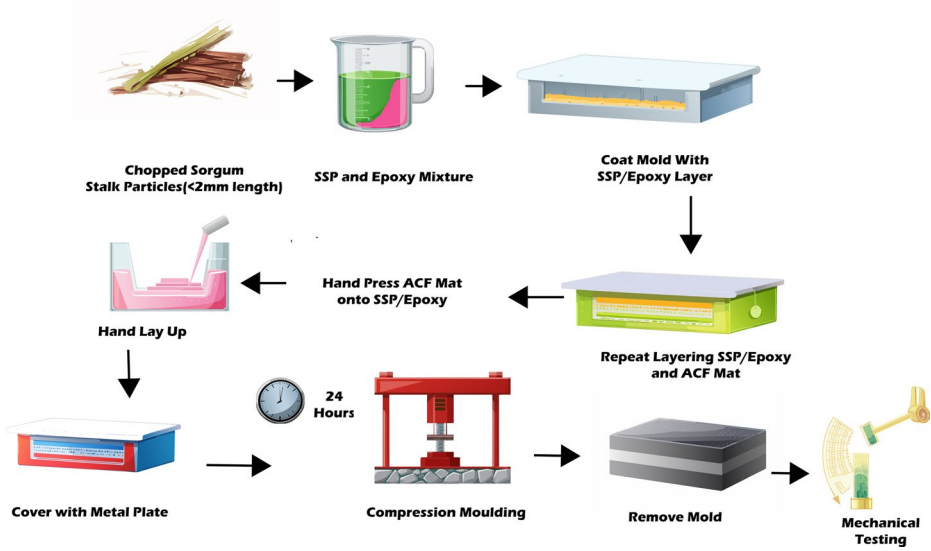


Fig. 1 Schematic of entire process

Table 1 Composition of material used in this study

Designation of sample	SS <sub>p</sub> (WRS)	AC (WAC)	Epoxy (W <sub>m</sub> )
S0 (Neat)	0	0	1
S1	0.04	0.18	0.78
S2	0.08	0.18	0.77
S3	0.12	0.18	0.70

## 2 Materials and methods

Kovai cheenu enterprises of Coimbatore, India, supplied the Epoxy HY951 and hardener LY556 mix utilized to prepare the test specimens. The AC plant and Sorghum Stalk were gathered from the nearby Erode district. Particles of cleaned and separated Sorghum Stalks are processed into Sorghum Stalk particles after being chopped into tiny pieces with a length of less than 2 mm. Using a water retting technique analogous to, the ACF is removed from the bark. A unidirectional fiber mat was constructed for the composite’s production after the extracted ACF was segregated. Hand layup was used to manufacture the composite. A coating of the prepared SSP and epoxy mixture is applied to the mold as the first step. The ACF mat is then hand-pressed onto this layer before being covered with an additional layer of the SSP and epoxy mixture. This process is carried out again and again until the laminate reaches the desired thickness. The last step is to place a metal plate over the mold’s top and let it cure for 24 h in room temperature and humidity. The last step was to take the mold out of the cured hybrid SSP/ACF composite which is depicted as schematic in Fig. 1. Table 1 displays the specifics of the mixed samples as well as the sample codes used to characterize them.

Several experimental investigations are conducted to learn how the mechanical and physical properties of the composite are affected by the fiber reinforcement. The numerical

density ( $\rho_i$ ) of the composite samples can be determined by applying the rule of mixture to Eq. (1). In this setting, the density ( $\text{g/cm}^3$ ) and volume percent of the matrix ( $V_m, f$ ) are denoted by the vectors  $\rho_{m, f}$  and  $V_{m, f}$  correspondingly. Equation (2) is used to obtain the experimental density ( $\rho_e$ ) by substituting the test samples' weight ( $W_s$ ) and the volume of water displaced ( $V_d$ ). The rise in water absorption with increased natural fiber content corroborates previous findings, attributing this to the hydrophilic nature of lignocellulosic materials [22]. Filling in the values of  $\rho_i$  and  $\rho_e$  from the composite samples into Eq. (3) estimates the voids in the test sample, while immersing the hybrid SSp/ACF composite samples in water for 72 h in compliance with ASTM D570 measures their WA. By plugging the values of  $W_1$  (g) for the starting weight and  $W_2$  (g) for the ending weight of the specimens into Eq. (4), we can determine the WA in the composite samples.

$$\rho_t(\text{g/cm}^3) = \rho_m V_m + \rho_f V_f \quad (1)$$

$$\rho_e(\text{g/cm}^3) = W_s/V_d \quad (2)$$

$$V_c(\%) = (\rho_t - \rho_e)/\rho_t \times 100 \quad (3)$$

$$WA(\%) = (W_2 - W_1)/W_1 \times 100 \quad (4)$$

By analyzing the material's mechanical properties, we can determine the created composites' strength and load bearing capacity. In line with ASTM E384, the microhardness of the hybrid SSp/ACF composite is evaluated using the Vickers hardness (HV) instrument. Vickers hardness testing was executed using a diamond pyramid indenter with a load of 500 gf applied for a duration of 10–15 s. A universal testing machine was used to measure the  $\sigma_i$  of the composite specimens in accordance with the testing requirements stated in ASTM D 3039. Using standard specimens at a steady crosshead speed of 1 mm/min, and average values were derived from several samples to ensure accuracy. A universal testing machine is used to assess the  $\sigma_f$  in accordance with ASTM D 790 standards, while an Izod impact tester is used to evaluate the  $\sigma_i$  in accordance with ASTM D4812 testing standard. Impact testing was performed with a standard impact testing machine in line with ASTM standards, and the absorbed energy values were documented. The test samples' mechanical characteristics were calculated using Eqs. (5, 6, 7, 8, 9, 10 and 11).

$$\text{Tensile strength, } \sigma_t(\text{MPa}) = F_m/A_c \quad (5)$$

$$\text{Tensile modulus, } \sigma_{tm}(\text{GPa}) = \Delta\sigma/\Delta\varepsilon \quad (6)$$

$$\text{Tensile strain, } \varepsilon_t = D/L \quad (7)$$

$$\text{Flexural strength, } \sigma_f(\text{MPa}) = (3F_m L)/(2w^2) \quad (8)$$

$$\text{Flexural modulus, } \sigma_{fm}(\text{GPa}) = (L^3 m)/(4wd^3) \quad (9)$$

$$\text{Flexural strain, } \varepsilon_f = 60 d/L^2 \quad (10)$$

$$Vickers\ Hardness, V_h (HV) = 1.854 * F_f / A_t^2 \tag{11}$$

The variables  $A_i$ ,  $A_c$ ,  $F_a$ ,  $F_m$ ,  $d$ ,  $L$  and  $w$ , stand for the area of indentation, cross-sectional area, applied force, maximal force, thickness, length, and width, correspondingly, in units of Newtons and millimeters squared. The variables  $D$  stands for displacement,  $m$  for the slope of the tangent to the initial straight-line part of the load-deflection curve, and  $\epsilon_t$  and  $\epsilon_f$  represent strain through tensile load and flexural load, according to their respective meanings.

### 3 Results and discussion

#### 3.1 Results on physical properties

The hybrid SSp/ACF composite’s  $\rho_t$  and  $\rho_e$  are displayed in Fig. 2. As the SSp concentration increased, a drop was noted in the  $\rho_t$  and  $\rho_e$  of the test specimens. The hybrid composites’ reduced density is a direct outcome of the relative low densities of SSp and epoxy. Compared to the tidy laminate, the S3 test sample had a 40% reduction in  $\rho_e$ . Additionally, the test samples had a smaller  $\rho_e$  than the  $\rho_t$ . This occurs because air and gaseous volatiles produced during manufacture create a porous structure. The study also found that the void percentage in the composite specimen was reduced with the inclusion of SSp. By filling the spaces between the intermediate ACF and epoxy zone, the porosity in the test sample was

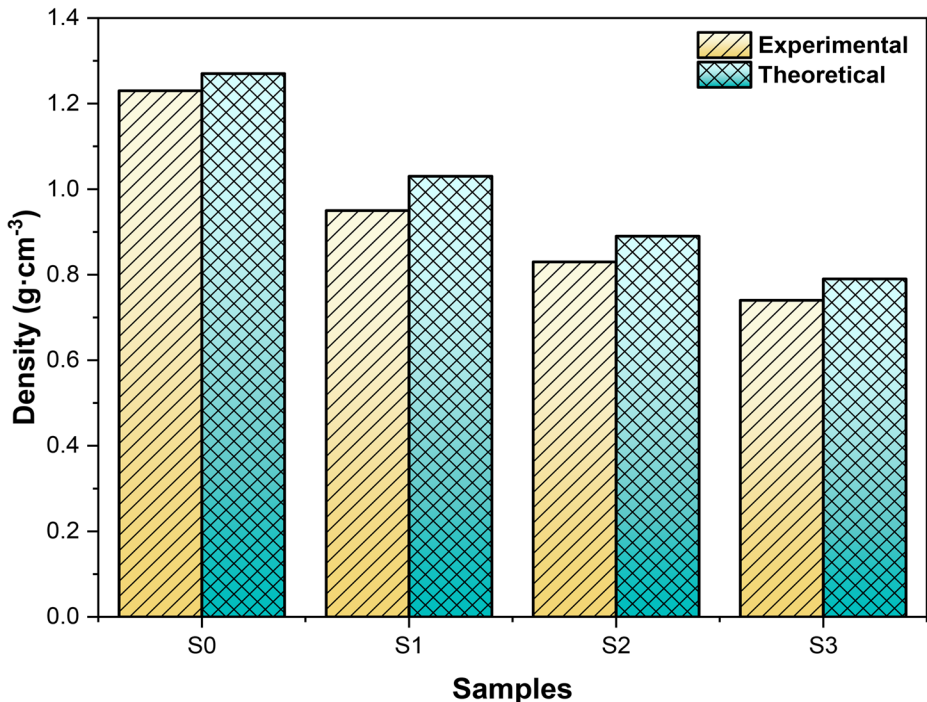


Fig. 2 Evaluation of density of the various composites

reduced as the SSp extended throughout the ACF mat. Compared to S1, the void content (%) of S3 composite is 18.51% lower.

### 3.2 Water absorption (WA)

Different test samples were evaluated at 24-hour intervals for 30 days, and the percentage of WA is shown in Fig. 3. Since the tidy composite is impervious to water, it did not absorb a significant amount of moisture. Because natural fibers are hydrophilic, adding them to epoxy raised the WA. Natural fibers' hydroxyl groups form hydrogen bonds in the cell walls of the fibers, allowing them to store water molecules. The number of hydroxyl groups rose and the moisture uptake accelerated as the concentration of natural fibers in the laminate increased. The WA in the hybrid test samples rose sharply (4–7%) in the first 24 h of immersion, and then raised steadily for the rest of the research period. The test samples were immersed in water continuously until they absorbed as much moisture as feasible. After 648 h, the WA in the samples became almost insignificant. During the 720-hour immersion period, the composite containing 12 wt% SSp exhibited the highest water absorption rate (WA) of 16.76%, while the neat composite exhibited the lowest WA of 0.092%.

### 3.3 Tensile properties of hybrid SSp/AC composites

Figure 4 shows the tensile modulus and tensile strength of composites composed of ACF and Sorghum stalk at different concentrations. The greatest tensile strength for the neat sam-

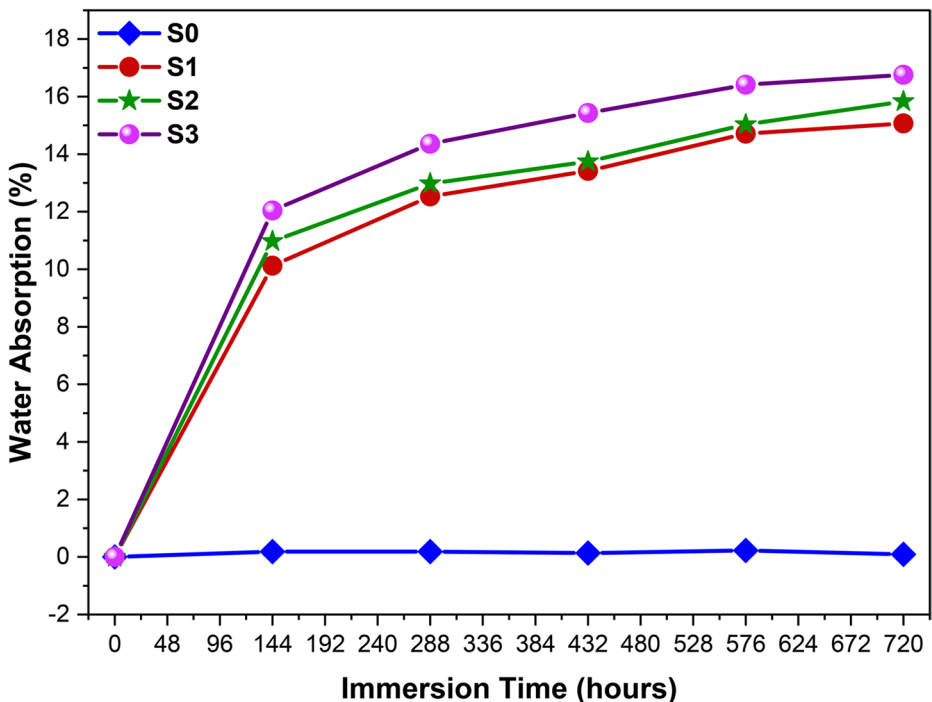
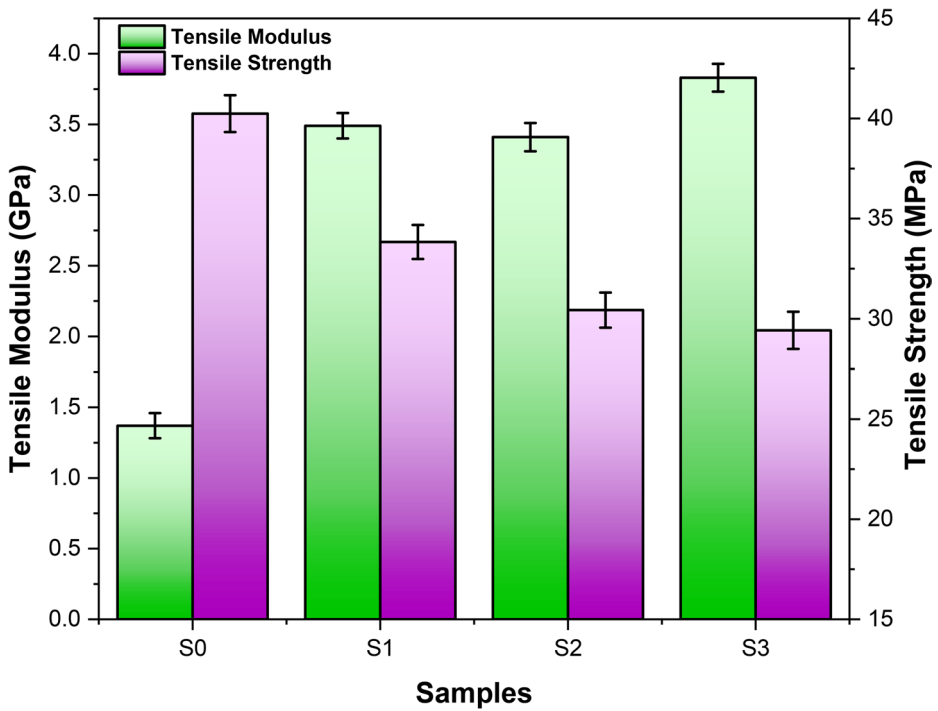


Fig. 3 Water absorption in SSp/ACF composite



**Fig. 4** Evaluation of tensile properties of the composites

ple was 40.24 MPa, while for the S1 it was 33.83 MPa. Because natural reinforcements provide greater inhomogeneity, the standard deviation of composites during tensile tests grows somewhat as fiber content increases. The SSp addition lowered the epoxy material's tensile strength. S3 composite has a 26.69% lower tensile strength than the plain sample. Stress concentration zones in the laminate formed by the interphase of SSp and epoxy allowed cracks to propagate through these interfaces when focused to a tensile strength (TS) load. The enlargement of these stress concentration zones reduced the tensile properties of the composite as the SSp content grew. The deprived moistening of AC fiber and frail interfacial bonding among the composite's mid-fiber phases were further effects of the higher SSp concentration that reduced the TS of the composites. For the reasons stated earlier, the neat composite had a higher overall TS than the hybrid SSp/ACF composite.

Figure 4 further shows that when the SSp level in the test samples grew, so did their tensile modulus. Increasing the SSp content from 4 to 12 wt% resulted in a slight improvement to the tensile modulus. A hybrid composite containing the maximum amount of SSp and ACF has a tensile modulus 64.23% more than pure epoxy. A tensile modulus of 3.83 GPa was observed in the S3 combination.

Tensile load stress-strain graphs for composites are displayed in Fig. 5. In comparison to hybrid composites, the clean sample exhibited the maximum strain at 0.029. The reason behind this is that the polymers had lower tensile modulus and hence more strain when subjected to a tensile load, which is caused by lower intermolecular connections. Yet, when 12 wt% SSp and 18 wt% ACF were added, the composite's maximum strain reduced. The

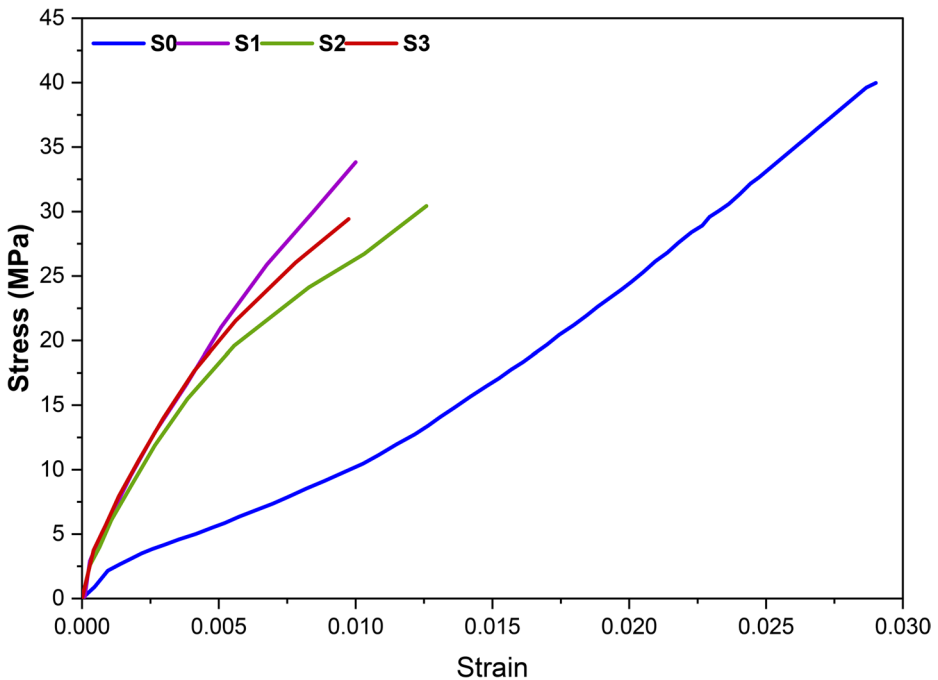


Fig. 5 Evaluation of tensile stress vs. strain of various composites

greater tensile modulus in the hybrid composite is a direct outcome of the natural fibers' rigidity, which created a higher composite stiffness.

### 3.4 Flexural properties of SS<sub>p</sub>/ACF composites

The flexural modulus and flexural strength of the specimens that were tested are displayed in Fig. 6. Incorporating SS<sub>p</sub> and ACF reinforcements into epoxy composites lowers their flexural strength and modulus, while the neat test sample outperforms hybrid composites in terms of flexural strength (116.36 MPa) and modulus (3.53 GPa). The reason behind this is that the fibers' load bearing capability is decreased when seen perpendicular to their axis. Even before the vacuums and poor interaction bonding among the matrix and fiber components made matters worse, the composite had a low flexural strength. It is worth noting that hybrid composites showed a small but noticeable improvement in flexural modulus and flexural strength as the SS<sub>p</sub> content increased. The increased stiffness of the laminate, brought about by the inclusion of SS<sub>p</sub>, is responsible for this enhancement since it postpones the crack onset under the applied flexural strain. A 14.67% improvement in flexural strength and an 11.64% improvement in flexural modulus were achieved when the SS<sub>p</sub> content was increased from 4 wt% to 12 wt% in the hybrid composite.

Figure 7 displays the test specimens that were subjected to a flexural load together with the stress-strain data for each specimen. It turns out that fiber reinforcement lowers the maximum strain that can be produced in the pure composite. Nevertheless, when compared to other composites, the hybrid SS<sub>p</sub>/ACF composite exhibited the highest strain (0.035)

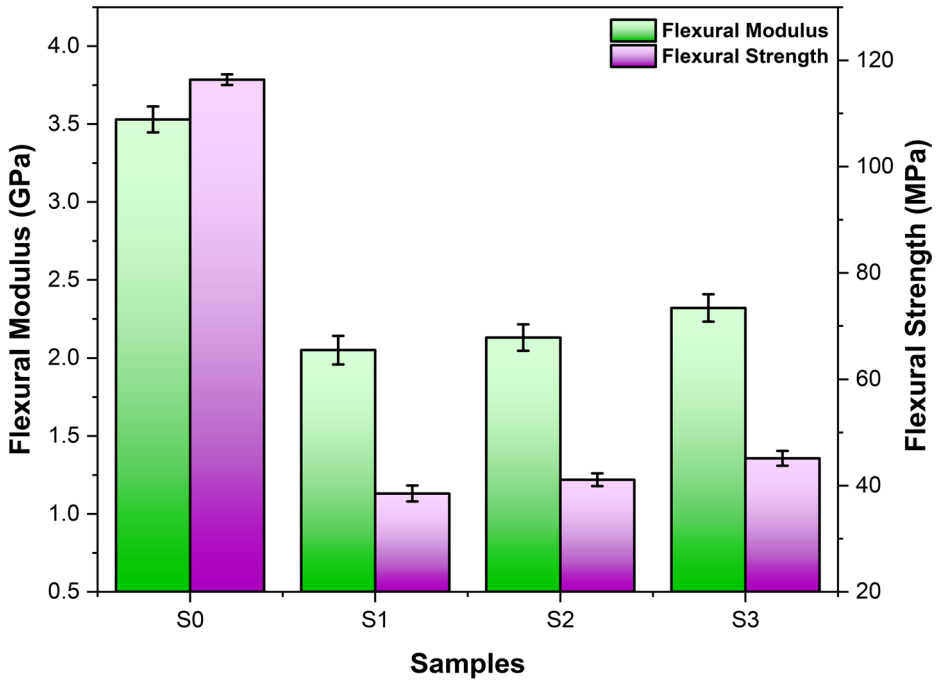


Fig. 6 Evaluation of flexural properties of various composites

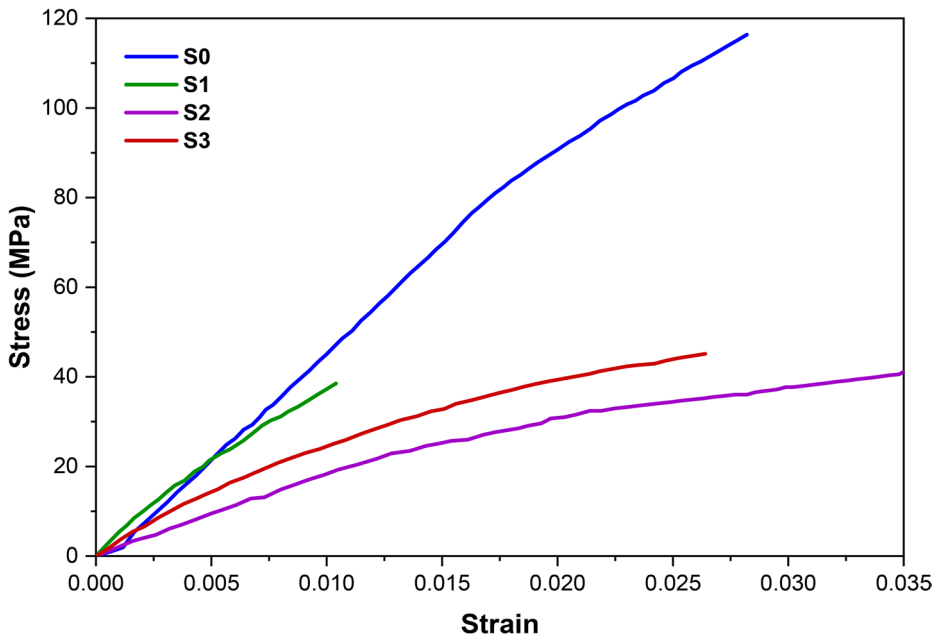


Fig. 7 Evaluation of flexural stress vs. strain plot of various composites

and a progressive increase in strain up to 8 wt% of SSp in the laminate. The inclusion of an optimal concentration of SSp in the laminate delays the fracture onset, which improves the strain. Increases in SSp content (> 8 wt% of SSp) led to inadequate fiber wetting, which in turn increased stiffness and decreased the laminate's maximum strain.

### 3.5 Impact strength

The impact strength of the hybrid SSp/ACF composite is illustrated in Fig. 8. The impact strength of the hybrid composite was found to be improved with an increase in the proportion of SSp from 4 wt% to 8 wt%, in conjunction with an 18 wt% ACF content in the matrix. An impact strength of 106.14 J/m is achieved in the hybrid composite at an SSp concentration of 8 wt%. After increasing the number of Sorghum Stalk particles from 8 wt% to 12 wt%, the impact strength was 25.08% lower than the peak impact strength achieved by the S2 composite. Beyond the ideal concentration of 8 wt%, adding more Sorghum Stalk caused the fibers to become improperly wetted and reduced the interfacial interaction between the matrix material and the fibers. Because of this, the final composite is less capable of absorbing and transferring impact loads. As a result, increasing the concentration of SSp weakens the impact.

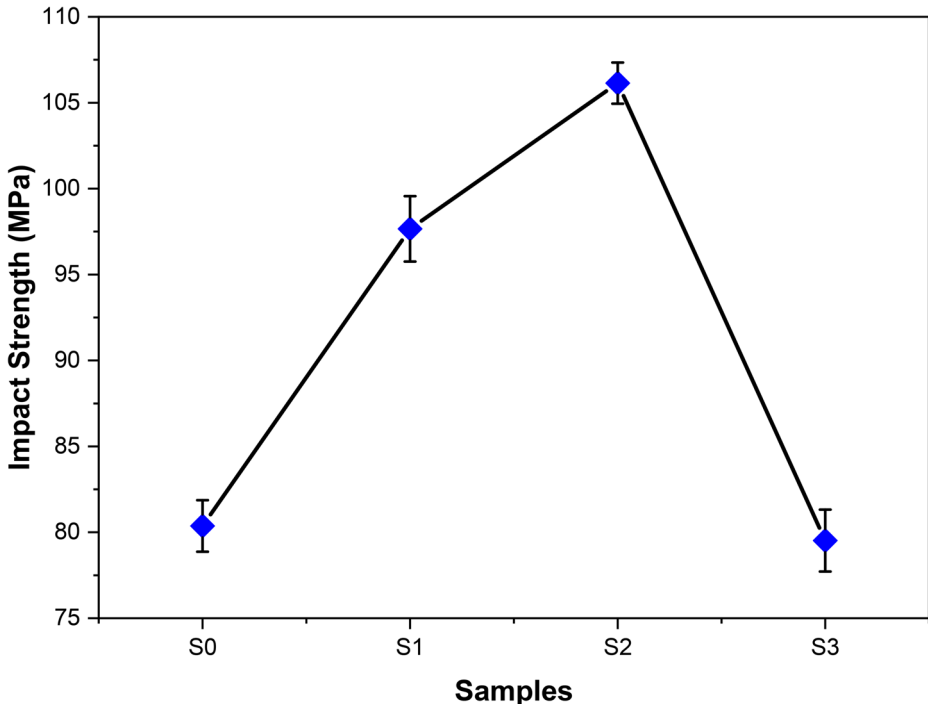


Fig. 8 Impact strength of SSp/ACF composites

### 3.6 Micro hardness

All three specimen types (neat, S1, S2 and S3) were tested for hardness, as shown in Fig. 9. Out of all the samples tested, the clean composite had the hardest surface at 25.63 HV. The toughness of the hybrid composites was reduced when the SSp content was increased. A very thin coating of epoxy covers the hybrid composite's top surface layer. Indentation causes the hybrid composite's surface load to be transmitted to the SSp, a material with lesser stiffness and relative softness than the cross-linked epoxy. Consequently, the SSp reinforcement lowers the epoxy material's overall hardness. Another theory that explains why hybrid composites aren't as rigid is that they have smaller filler particles and surface micro gaps. Adding 12 wt% SSp to epoxy reduced the composite's hardness by 40.34%.

### 3.7 Morphological study of fractured surfaces

There were no signs of cracks or delamination on the cut surface, and the test sample failed nearly vertical to the matrix fiber axis.

Figure 10 (a) shows that the ACF were broken at the failure line, but they remained completely undamaged in the epoxy, which means that the ACF and matrix had a good interphase. Figure 10 (b) shows that the test samples catastrophically failed brittlely because the fracture propagated so quickly in the hybrid laminates because of their increased ductility. The SSp exhibited debonding in the areas where the material failed; this is because the fibers were too short to remain attached to the epoxy when it failed. Figure 10 (c) shows that

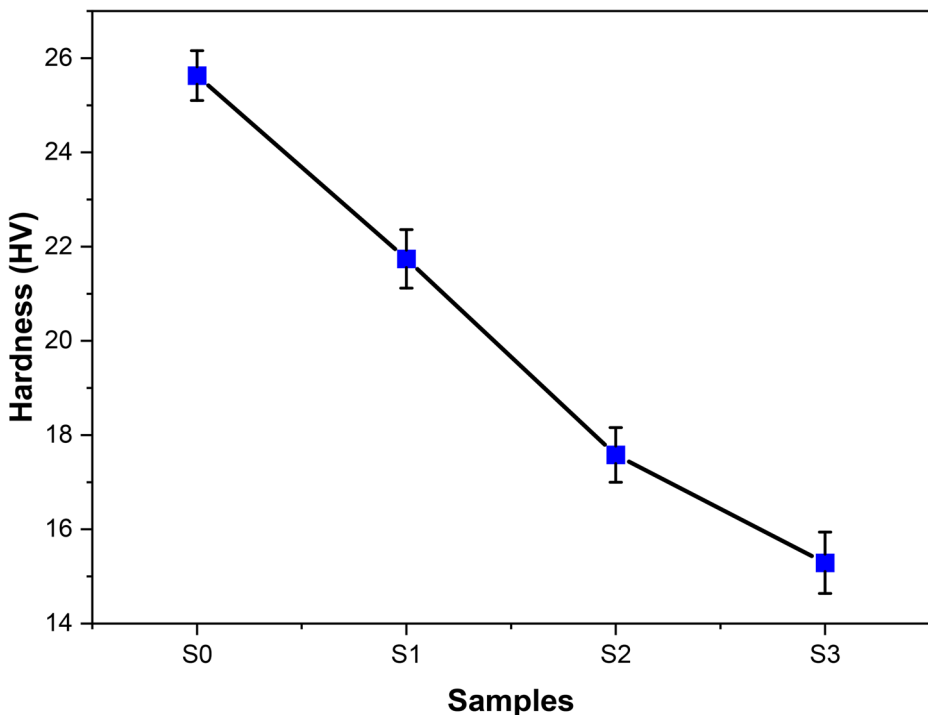
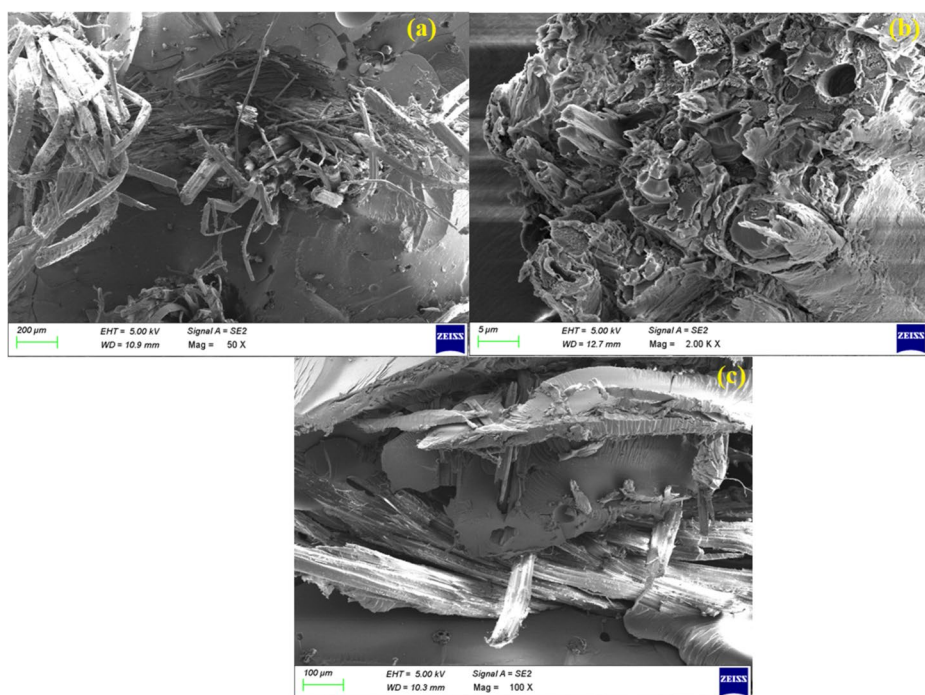


Fig. 9 Evaluation of hardness of SSp/ACF composites



**Fig. 10** SEM analysis of tensile failure region of composites (a) S1 (b) S2 and (c) S3

the SSp in the direction of matrix failure are shown to be separated along the fiber axis. The ACF and matrix material remained intact in the test samples even after being subjected to the flexural strain. It seems that the entire laminate layer was distorted at the loading point as a result of the applied load, which caused the top fiber layer to move and delamination on top. Fiber pull-out is greater in the samples with 4 and 8 wt% SSp, but significantly lower in the test sample with 12 wt% SSp. The test specimen with 12 wt% SSp had a cut surface shear angle of about  $14.51^\circ$ .

## 4 Conclusions

The current research successfully created a hybrid composite by reinforcing it with sorghum stalk particles and Acacia caesia fibers through the hand lay-up method. In order to study the mechanical and physical characteristics of the hybrid SSp/ACF composite, the percentage of SSp in the laminate is varied during the manufacturing process. There is a 40% reduction in density when comparing neat epoxy composite to SSp and ACF reinforced hybrid composite. When immersed for longer periods of time, the hybrid composites absorbed more water, reaching a saturation threshold after more than 648 h. During the first 24 h, the greatest absorption rate was 5.55%. A combination of SSp and ACF reinforcements made the composite much more rigid and ductile. The optimal concentrations for SSp and ACF were found to be 4, 12, and 18 wt% when tested against other combinations. At this concentration, the maximum tensile strength was 29.42 MPa, the impact strength was 106.14 J/m,

and the flexural strength was 45.12 MPa. When chopped SS<sub>p</sub> reinforcement was added, it lowered the mechanical characteristics of the hybrid composite by creating zones of intermediate stress concentration. The multidirectional ACF composite outperformed the hybrid SS<sub>p</sub>/ACF composite in terms of  $\sigma_t$  (8.46%) and  $\sigma_f$  (42.49%). Under the microscope, the SS<sub>p</sub>/ACF composite's shattered surfaces revealed brittle cracks, but no fiber pull-out. This study emphasizes the potential of integrating agricultural waste particles with natural fibers to produce hybrid composites with enhanced properties, presenting an innovative approach to sustainable material design. The resulting hybrid composite shows promise as a light-weight, economical, and sustainable material suitable for structural and engineering uses.

**Author contributions** Conceptualization and Methodology: C. G., Investigation and Data curation: S.V., Investigation, formal analysis: R.P., Writing—review and editing: S.K., Supervision and Data curation: S.M., D. S. B.

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**Data availability** No datasets were generated or analysed during the current study.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate and publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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