



Assessment of Soil and Fungal Degradability of Thermoplastic Starch Reinforced Natural Fiber Composite

Ajaya Kumar Behera¹ · Chirasmayee Mohanty¹ · Sibun K. Pradhan¹ · Nigamananda Das¹

Accepted: 19 October 2020 / Published online: 26 October 2020
© Springer Science+Business Media, LLC, part of Springer Nature 2020

Abstract

High water absorption capacity and low biodegradation of fiber reinforced composites are the major drawbacks, which limit their applications in different sectors. Development of composites with complete biodegradability is challenging as biodegradability may be incomplete by lowering of its water adsorption capacity. In this work, a series of thermoplastic starch (TPS) reinforced jute (10–40 wt%) composites were developed by compression molding and measured by their mechanical properties. The composite with 30% jute showed the maximum tensile strength (27.3 MPa). Contact angle, and water absorption measurements exposed that composites are moderately hydrophobic in nature. Both soil burial and fungal degradation testing showed biodegradability of composites. Characterizations of optimized composite before and after biodegradation test, were carried out by FTIR, SEM and optical microscope. The present study showed promise on feasible applications of jute-starch composites in packaging, automobile sector, cutlery, indoor furnishing, etc. as a substitute of plastic-based composites.

Keywords Biodegradable polymer · Natural fiber · Mechanical properties · Biocomposite · Fungal degradation

Introduction

Starch, a natural polysaccharide available in different plant resources, is an important substitution for synthetic polymers for various applications. The hydroxyl group of starch can form bond with the functional group of natural fiber [1]. As starch alone cannot meet all the required properties for practical applications, it is often blended with another component like plastics (e.g. polyester) to develop thermoplastic starch (TPS) for wider applications. Blending of starch with a non-biodegradable plastic not only promote the biodegradability of that plastic but also acceptable as a matrix for reinforcement of natural fiber or clay to develop bio-composites [2].

In this regard several researchers have explored the interaction between starch and different natural fibers to develop biocomposites and assessed their properties [2–4]. Starch reinforced composite using different natural fibers such as jute, sisal, and cabuya (0 to 15% w/w) have been developed and the composites with 12%

fiber loading showed the highest tensile strength. Further increment in fiber content decreased the tensile strength primarily due to the formation of voids and fiber clumps in the specimens. Wood cellulose fiber was used with starch to develop bio-composites and it showed higher rigidity and tensile strength, but lower elongation at break and poor water penetration stability over cellulosic fiber film [3]. Recently sisal fiber (65% w/w) reinforced starch (40 wt%) composites have been prepared, which demonstrated low impact strength because of poor interaction between fiber and matrix [4]. In another study, the composites prepared from rice starch with 10 wt.% cotton fiber showed two times more tensile strength as compared to that of the virgin cotton fiber, but decreased on further incorporation due to the discontinuity of the matrix on fiber surface [5]. Increase of tensile modulus and strength of thermoplastic starch-eucalyptus cellulosic composites by 156% and 120%, respectively with 16% w/w of fiber content, and simultaneous decrease of moisture absorption capacity from 22% to 15% as compared to cellulosic fiber have been reported [6]. In contrast, marginal increase on tensile and flexural strength were noted for natural fiber-reinforced (sisal and hemp fiber) thermoplastic starch with glycerol composites with increase in percentage of reinforcement [7]. Thermoplastic starch

✉ Ajaya Kumar Behera
ajayabehera@utkaluniversity.ac.in

¹ Department of Chemistry, Utkal University, Bhubaneswar, Odisha 751004, India

reinforced wood composites were developed and found higher water uptake due to lose interfacial adhesion between reinforcing fiber and matrix [8]. Synthesis of thermoplastic starch reinforced composites by foam molding process using four different kinds of natural fibers such as straw, pulp, sisal and wood, has been reported [9]. In this study, the sisal composite showed the highest thermal stability among all with tensile strength of 3.85 MPa and compressive strength of 1.37 MPa, respectively due to better reinforcing [9].

In view of above, synthesis and property evaluation of composites based on other starch and natural fiber is important to develop the composite(s) with correct constituents for wider applications. In this work, the corn starch blended with aliphatic polyester (TPS) was used in different *w/w* percentage with jute felt to develop jute-TPS composites. The prepared composites were characterized by different techniques and their biodegradability was studied by soil burial and microbial degradation testing. As compared to others reported work, the research work in this manuscript is completely different as developed composites are complete biodegradable in nature with lower water absorption capacity. Since these composites are biodegradable and leave safe carbon residue after complete biodegradation, so they can be dumped to form effective organic manure and improve fertility of soil without harming environment. These composites may find application in different sectors i.e., as decorating materials, false sealing, and workplace cubicles as a replacement of non-biodegradable plastics. A schematic representation of the experimental setup for jute-TPS composite development to usage has been given in Fig. 1.

Materials and Methods

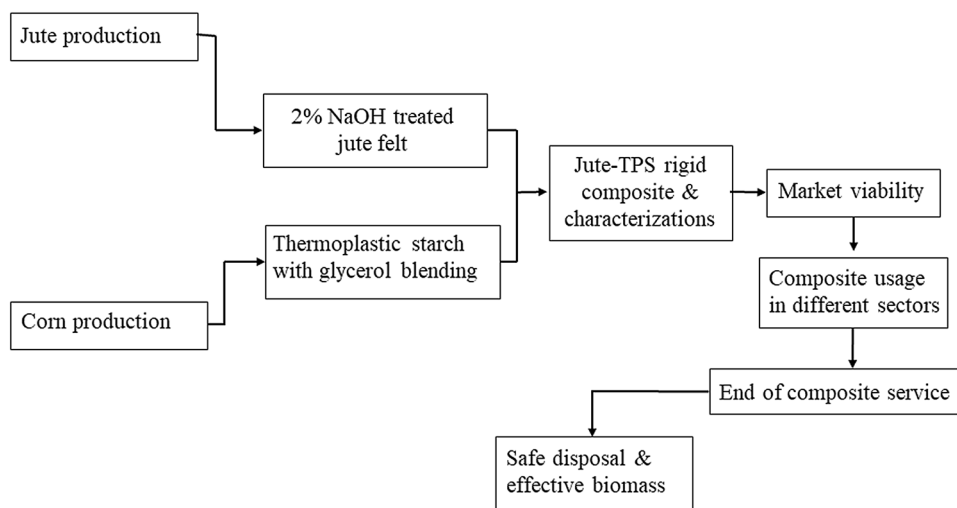
Materials

Jute felt (non woven 400 gsm), collected from local market of Bhubaneswar, India, was used as a reinforcing material. Thermoplastic starch (TPS) was used as matrix was supplied by Biograde (Nanjing) Pty, China. The TPS was formed by blending corn starch with poly(ϵ -caprolactone) along with natural plasticizers. The basic resin, corn starch, is a renewable material and compiled with International standard ISO-16929 and ISO-14855. Glycerol and sodium hydroxide used were of AR grade and brought from local market.

Preparation of Jute-TPS Composites

Blends of TPS with glycerol (5 wt.%) were prepared by melt mixing at 100 °C with 60 rpm stirring for 5 min using double screw extruder of an internal mixer (Brabender mixing chamber) [1]. Jute felts (400 GSM) was first dipped in 2% NaOH solution for 2 h to activate the cellulosic functional group as shown in Fig. 2a, followed by drying at open air for 1 h and then cutting into pieces of size 15 cm × 15 cm. A series of composites were prepared with jute: TPS ratio (*w/w*) 10:90, 20:80, 30:70 and 40:60. At first the TPS blend was put on an aluminum foil placed in the mold and then a piece of jute felt was kept over TPS followed by another layer of TPS blend and finally covered with aluminum foil. The mold was placed in a hot press and applied a pressure of 6 MPa at 110 °C for 10 min to obtain the requisite Jute-TPS (JT) composites. The composites so prepared were coded as JT1, JT2, JT3 and JT4 for sample with jute: TPS ratio (*w/w*) 10:90, 20:80, 30:70 and 40:60, respectively.

Fig. 1 A schematic representation of the jute-TPS composite development and usage



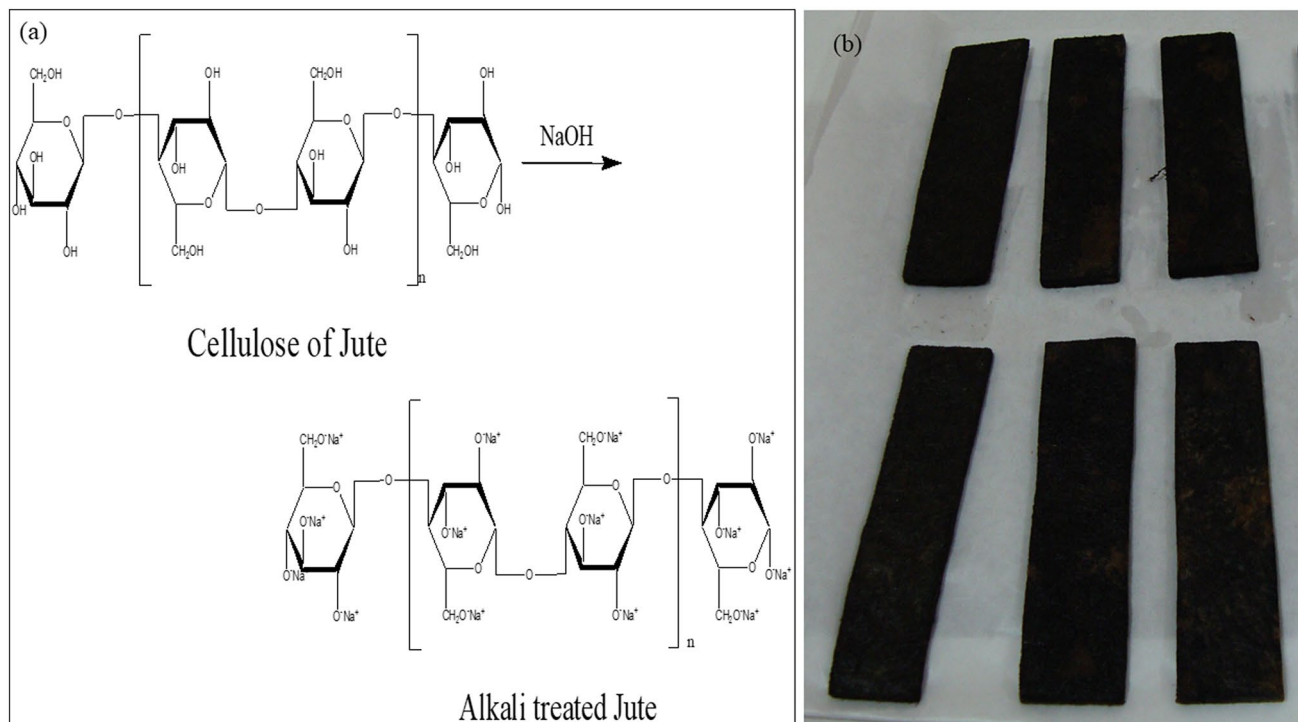


Fig. 2 (a) A schematic representation of alkali treatment of cellulose of jute, (b) Digital photograph of soil burial degraded samples

Mechanical Properties Analysis

Mechanical properties of JT composites and virgin TPS were measured using a HOUNSFIELD H10KS UTM instrument. For measuring tensile strength, the cross-head speed maintained at 5 mm/min and the specific gauge length at 50 mm respectively, whereas for flexural testing cross-head speed was 2 mm/min. Six specimens of one sample were examined and the mean value was reported [10].

Contact Angle and Water Sensitivity Study

SEO Contact angle meter was used for measuring contact angles of JT composites. At least seven places on composite surface are preferred for the testing and mean value in degree is conveyed.

JT composites were tested for water absorption with respect to jute and TPS according to ASTM D570–05. Composite specimens were cut into small pieces of specific dimension and initial weights (W_i) were measured. Different samples were kept in distilled water at room temperature for a fixed time interval (24 h). After that specimen was taken out of the water and excess water on surfaces were wiped out using tissue paper. Final weight (W_f) of samples was measured and using the Eq. (1) hydrophilicity of composites were calculated:

$$\text{Water absorption (\%)} = 100 \times \frac{W_f - W_i}{W_i} \tag{1}$$

Similarly, thickness swelling of specimens after different time intervals was calculated by the following equation:

$$\text{Thickness swelling (\%)} = 100 \times \frac{T_f - T_i}{T_i} \tag{2}$$

where, T_i and T_f are the initial and final thickness of the specimen.

Thermal Analysis

thermogravimetric analysis (TGA) of Jute, TPS and JT3 composite were investigated by using Netzsch (TGA-209F) in the temperature range 32 ± 1 to $500 \text{ }^\circ\text{C}$ in air atmosphere and at a heating rate of $10 \text{ }^\circ\text{C}/\text{min}$.

Soil Burial Degradation Analysis

Soil burial degradation of different samples was conducted as per BIS 1623–92. For this test, $10 \text{ cm} \times 5 \text{ cm}$ sample was taken and accurately weighed (W_0). Specimen to compost soil (manure: sand: soil in 2:1:1) weight ratio was maintained at 1:100 (w/w) and the samples were buried under compost soil within a glass jar keeping moisture content

36%. After stipulated times (7, 15, 30, 45 and 60 days), specimens were collected, washed with water and dried at 45 °C in an oven for 24 h and final weight (W_1) was taken. Digital photograph of degraded sample is given in Fig. 2b. The percentage weight loss of composites was calculated by using Eq. 3.

$$\text{Weight loss (\%)} = 100 \times \frac{W_0 - W_1}{W_0} \quad (3)$$

Fungal Degradation Analysis

Penicillium waksmanii, was used for fungal degradation of composites. In Czapek Dox Broth, fungal stock cultures containing different mineral salt solution were taken as reported [11]. Composites were pre-weighed (W_0) and mixed with spore suspension of *Penicillium waksmanii* (1:10 w/v) in different petridish. Then these petridishes were incubated at 30 °C in an incubator-cum-humidity chamber maintaining 80% humidity for maximum 60 days. Composite samples were removed from above petridish after stipulated times (7, 15, 30, 45, and 60 days) and washed in ethanol to remove cell mass from the residual sample and dried in oven at 45 °C for 24 h. Final weight (W_1) of the composites was taken and using Eq. 3, weight loss was calculated.

FT-IR, SEM, and Optical Microscopic Studies of Neat and Degraded Composites

FT-IR spectra of as prepared JT3 and JT3 after soil and microbial degradation were taken in KBr pellet using a Thermo Nicolet, Nexus 870 IR spectrometer. The spectrum was recorded in the range 4000–400 cm^{-1} and averaging 32 scans to improve signal to noise ratio.

Morphological studies of Jute, TPS and representative composite samples (JT3 and JT4), before and after soil and micro burial degradation, were carried out using a SEM (VEGA II, LSU, TESCAN, Czech Republic) with accelerating voltage between 5 and 10 kV. Optical microscopic

study of jute and JT3 composite was taken before and after degradation, by an optical microscope (Leica DMLM 2500) and micrographs are reported. FT-IR, SEM and optical study of composite (JT3) showing the best mechanical properties was only carried out.

Results and Discussion

Tensile and Flexural Testing of Jute-TPS Composites

The outcomes obtained on various testing of mechanical properties of JT composites are presented in Table 1. As evident from Table 1, the tensile strength of composite increased with increase of jute content, reached to maximum value with 30 w/w jute (JT3) and then decreased on further increase of jute content. That is due to the mechanical interlocking was enough for JT3 to transfer the applied stress from the starch surface to the jute fibres. For JT1 and JT2, low amount of jute content caused little load transfer capacity among the fibers, which led to quick failure of the composites [12]. Chemical composition also affects the strength of the composite, as jute contains nearly 65% of cellulose, hence with increase in cellulose content (from JT1 to JT3), mechanical properties also enhanced. Marginal enhancement in tensile strength initially indicated that formation of essential adhesion between fiber–matrix interface due to the presence of similar functional group of starch and the cellulosic (jute) fiber. This development could be linked to strong jute–TPS matrix interaction between the two carbohydrate products. A schematic mechanism of formation of chemical bonding between jute and TPS is shown in Fig. 3. This type of interaction regarding other natural fiber has been reported earlier [13]. Starch, a carbohydrate consists of amylose, and amylopectin. They contain a lot of active functional groups, which help to form hydrogen bonding with that of the cellulose of jute [10]. That chemical linkage attributes strength to the developed jute-starch composite.

The tensile strength of JT3 (27.3 MPa) is eight times higher than that of virgin TPS (3.31 MPa). The tensile

Table 1 Mechanical properties of Jute-TPS composites

Composite	Jute (wt%)	TS \pm SD (MPa)	TM \pm SD (MPa)	EB \pm SD (%)	FS \pm SD (MPa)	FM \pm SD (MPa)
Jute	–	320 \pm 25	20,000 \pm 650	1.5 \pm 0.2	–	–
TPS	–	3.31 \pm 0.2	53.2 \pm 5	8.2 \pm 0.20	3.21 \pm 0.3	55 \pm 5
JT1	10	12.2 \pm 1.2	102 \pm 11	9.1 \pm 0.38	9.75 \pm 2.0	158 \pm 15
JT2	20	22.8 \pm 1.5	235 \pm 12	7.8 \pm 0.41	11.9 \pm 1.9	169 \pm 18
JT3	30	27.3 \pm 1.3	296 \pm 13	7.6 \pm 0.44	13.2 \pm 2.3	178 \pm 16
JT4	40	24.5 \pm 1.6	335 \pm 12	7.2 \pm 0.29	10.9 \pm 1.8	72.7 \pm 13

TS tensile strength, TM tensile modulus, EB elongation at break, FS flexural strength, FM flexural modulus, SD standard deviation

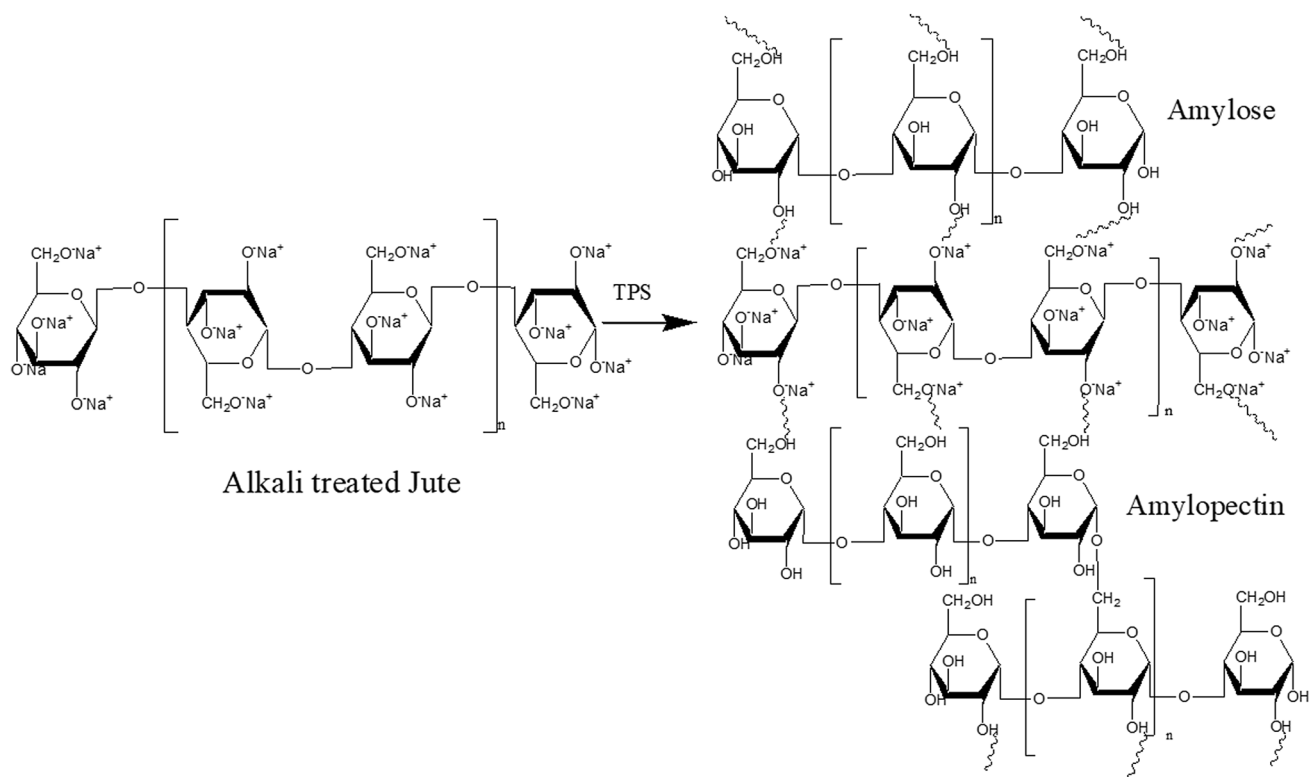


Fig. 3 A schematic representation of bonding between alkali treated cellulose of jute and amylose and amylopectin of starch

strength is nearly equal to that of the reported jute-polypropylene composite (28.4 MPa) [14]. Decrease of tensile strength of composite (JT4) on further increase of fiber content may be attributed to inadequate wetting of TPS on jute surface or conglomeration of jute inside composite destroyed the homogeneous interlocking with resin. A continuous non-linear increase of tensile modulus is, however, observed with the increase of jute content. Further, the elongation at break value decreased from 9.1 to 7.2 with increase in jute loading presumably due to increase in fiber stiffness and high amount of fiber leads to additional stress to break the composite earlier as compared to other composites [12]. The flexural strength and modulus of composites also followed the similar trend as that of tensile strength showing highest values 13.2 MPa and 178 MPa with JT3 (30 wt.% of jute) respectively. Highest fiber content JT4, showed flexural strength of 10.9 MPa might be due to the small spacing between jute fibers causes inefficient stress transfer between jute and TPS. That accounts an early failure of composite due to increased shear stresses on the jute fibers. The tensile strength obtained from jute-TPS composite is the modest one but higher than that of the reported value (26.1 MPa) of other jute-starch composite [15], hence JT composites can be applied in various fields as a substitute of plastic.

Surface Morphology Analysis of Jute-TPS Composites

SEM of JT3 composite along with jute fiber and TPS were carried out to see the morphological changes taken place due to formation of composite and micrographs are presented in Fig. 4a–c. From Fig. 4a, it is evident that the surface of reinforcing alkali treated jute fiber is smooth and provides large surface area as compared to raw jute fiber due to unbinding of fibrils for resin impregnation. The surface of thermoplastic starch is also smooth and without any damage. Figure 4c presents the micrograph of long jute fiber entrenched and the fiber surface is wetted by the TPS matrix. It is seen that fibers are spread in the matrix homogeneously. The jute surface covered by matrix indicates the solid bond between the fiber and starch [11]. SEM micrographs presented in Fig. 4c confirmed, that during the tensile breaking some cracks are developed and propagated around jute fiber in the matrix confirming the morphological changes during tensile test. The initial surface of starch and jute fiber changed into a homogeneous and continuous surface such that stress can propagate from fiber to matrix. This observation is indicative of a good adhesion between fibers to matrix.

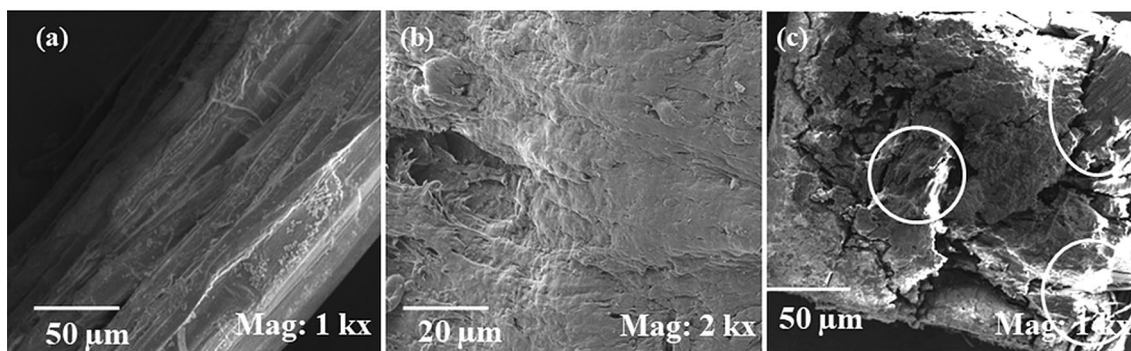


Fig. 4 SEM micrographs of (a) jute (b) thermoplastic starch and (c) fractured JT3 composite

Table 2 Water sensitivity of Jute-TPS composites

Sample	Jute	TPS	JT1	JT2	JT3	JT4
CA (°)	42.6 ± 1.2	97.1 ± 0.8	93.2 ± 0.5	90.4 ± 0.4	88.1 ± 0.7	84.6 ± 0.8
WA (%)	190 ± 2.5	6.1 ± 0.5	11.2 ± 0.2	14.9 ± 0.4	15.4 ± 0.5	22.2 ± 0.5
TS (%)	–	5.4 ± 0.5	10.8 ± 0.9	14.6 ± 1.2	16.2 ± 0.8	22.4 ± 1.2

CA contact angle, WA water absorption, TS thickness swelling, TPS thermoplastic starch

Contact Angle, and Water Absorption of Composites

For different applications of starch-based composites, lower water sorption value is necessary. The results of water sorption (after 24 h at RT & RH), and contact angle values are collected in Table 2. Water absorption was dramatically enhanced with the incorporation of higher amount of fiber loading due to the fact that jute fiber is more hydrophilic than thermoplastic starch resulting higher water uptake [11]. The observed values of contact angle (CA) for jute, TPS, and their composites are presented in Table 2. As evident, the presence of hydrophilic fiber in the composite decreased the CA value. Jute and TPS show the CA values of 42° and 97.1° respectively. According to Ufere and Sultan, (2016), poly(caprolactone) is hydrophobic in nature, having average water contact value of $115.1 \pm 2.6^\circ$, when it blends with hydrophilic material, CA value decreases [16]. JT1 have 93.2° hence, developed composite is more hydrophilic in nature as compared to its primary constituent TPS [17]. The effect of fiber contents on the water absorptivity and thickness swelling of composites enhanced proportionally. Compatibility and amount of fiber and matrix are one of the factors of such thickness swelling of JT composites. JT4 exhibited thickness swelling of 22.4% after its immersion in distilled water for 24 h due to highest amount of jute and poor interaction between jute and TPS. While, JT1 showed only 10.8% due to lowest amount of jute present and the hydrophobic nature of TPS which helps the slow diffusion of the water molecules within the composite. Other composites displayed the instability in thickness swelling enlarged due to higher percentage of jute and micro voids.

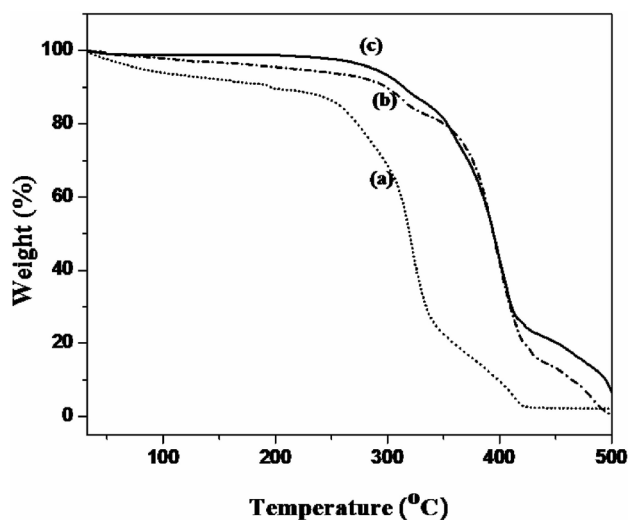


Fig. 5 Thermogravimetric curves of (a) jute, (b) thermoplastic starch, and (c) JT3

Thermogravimetric Analysis

Thermogravimetric curves of jute, TPS and JT3 composite are presented in Fig. 5. As evident there is no weight loss for both TPS and JT3 up to 100 °C while weight loss of jute in this range is primarily due to evaporation of its moisture content. As expected, jute showed two stage decompositions with maximum weight loss occurred in the range 280–420 °C. In contrast the decomposition patterns of TPS and JT3 are more or less similar except higher percentage of weight loss (ca. ~10%) in case of TPS. The first major

weight loss of TPS occurs at 310 °C corresponds to decomposition of polyhydroxylic groups while second loss, occurs at 397 °C, is attributed to high molecular weight groups present in the starch. The JT3 composite also decomposed, first at 312 °C due to the elimination of polyhydroxylic groups and second at 398 °C for cellulose. For all three samples, the decomposition in the range 480–495 °C is attributed to either some presence of metal or carbon burning as reported previously [1, 18].

Degradation Analysis of Jute-TPS Composites

Weight loss after different bio-degradation of JT composites with respect to jute and TPS are reported in Table 3. The total soil burial degradation in the case of pure TPS is 16.6 wt.% out of which ~50% wt. loss occurred within fifteen days. In comparison, both jute and composites showed increasing wt. losses up to 60 days. The initial low wt. loss of TPS is accounted due to the presence of aliphatic polyester which restricted the attack of soil microbes in soil burial studies [19]. In contrast, lower soil degradation of JT sample in early period of time may be attributed to slower absorption of water due to better fiber-resin crosslinking. Krasowska et al. (2016) studied the biodegradation of poly(caprolactone) and found 5.6% wt. loss after 2 weeks due to favorable biotic and abiotic conditions [20]. Virgin jute lost its 63.8 wt.% within 60 days as compared to only 22.8 wt.% of JT1. The percentage of degradation increased with increase of jute content and a maximum 45.6 wt.% degradation is observed in case of JT4 followed by 43.9 wt.% for JT3. The increasing wt. loss from JT1 to JT4 is obviously due to increasing jute fiber content which enhanced free path for microbial growth and easy degradation [21]. Presence of micro voids in composite due to higher amount of jute loading might be another reason for easy water penetration

and microbe attack. In microbial condition after 60 days, JT1 composite lost only 10.1% of its initial weight due to better stability against water penetration which hindered fungal growth on the composite surface. Jute fiber lost 25.4%, TPS 9.2%, JT3 12.6% after 60 days of microbial degradation informing that developed composites are degradable in both soil burial and microbial condition.

Spectral and Morphological Analysis of Composite Before and After Degradation

In order to study the effect of the degradation, FT-IR spectra of (a) neat JT3, (b) JT3 after 60 days of soil burial degradation and (c) JT3 after 60 days of microbial degradation were recorded and are shown in Fig. 6. Overall, the intensities of different peaks of neat JT3 composite are reduced after soil or microbial degradation. The intensity broad peak, centered at $\sim 3420\text{ cm}^{-1}$ due to $-\text{OH}$ stretching, is reduced after the degradation due to rupture of cellulosic hydroxyl group. Also, the intensities of peaks appeared at 2700 cm^{-1} and 2900 cm^{-1} due to C-H stretching (Fig. 6a) are reduced due to loss of cellulose and hemi-cellulose content after degradation. The intensities of characteristic peaks for C=O stretching (1734 cm^{-1}) and bending of CH_2 group (1270 cm^{-1}) of hemi-cellulose present in jute are also reduced indicating the degradation of hemi-cellulose by soil microbes. The intensities of C–O stretching band of C–O–C moiety in starch at 1000 cm^{-1} and C–C and C–O–H stretching bands of JT3 at $\sim 1165\text{ cm}^{-1}$ are seen to be reduced after degradation, indicating loss of resin from composite surface [22].

The SEM micrographs of jute, TPS, JT3 and JT4 composites, before and after 60 days of degradation are shown in Fig. 7. Cylindrical smooth surface of jute (Fig. 7a) and flat smooth surface of TPS (Fig. 7b) changed into rough and degraded surface (marked in Fig. 7e and f) after 60 days.

Table 3 Weight loss of jute-TPS composites after soil burial and microbial degradation

Type of Degradation	Weight loss	7 days (%)	15 days (%)	30 days (%)	45 days (%)	60 days (%)
Soil Burial	JF	22.4 ± 0.8	40.9 ± 1.7	59.6 ± 1.6	62.7 ± 2.3	63.8 ± 2.8
	TPS	3.4 ± 0.5	8.2 ± 0.4	12.6 ± 0.8	15.9 ± 0.7	16.6 ± 0.7
	JT1	5.2 ± 0.8	12.4 ± 0.6	18.1 ± 0.2	20.2 ± 0.7	22.8 ± 0.4
	JT2	6.9 ± 0.3	13.2 ± 0.1	20.5 ± 0.9	31.8 ± 0.8	34.2 ± 0.5
	JT3	9.1 ± 1.4	13.7 ± 0.9	23.2 ± 0.6	36.7 ± 0.2	43.9 ± 0.9
	JT4	10.8 ± 0.6	14.0 ± 0.5	25.5 ± 0.9	40.4 ± 3.1	45.6 ± 1.2
Fungal	JF	6.2 ± 0.4	10.6 ± 0.6	15.2 ± 0.6	22.1 ± 0.5	25.4 ± 0.7
	TPS	1.1 ± 0.5	3.6 ± 0.4	5.5 ± 0.3	6.8 ± 0.4	9.2 ± 0.5
	JT1	1.9 ± 0.1	4.5 ± 0.2	6.9 ± 0.4	7.8 ± 0.6	10.1 ± 0.5
	JT2	2.4 ± 0.3	4.8 ± 0.3	7.2 ± 0.5	9.3 ± 0.3	11.8 ± 0.2
	JT3	2.5 ± 0.4	5.2 ± 0.4	8.1 ± 0.4	10.2 ± 0.6	12.6 ± 0.4
	JT4	2.7 ± 0.2	5.9 ± 0.5	8.7 ± 0.3	11.1 ± 0.5	13.5 ± 0.6

W Weight, JF Jute Felt, TPS Thermoplastic starch

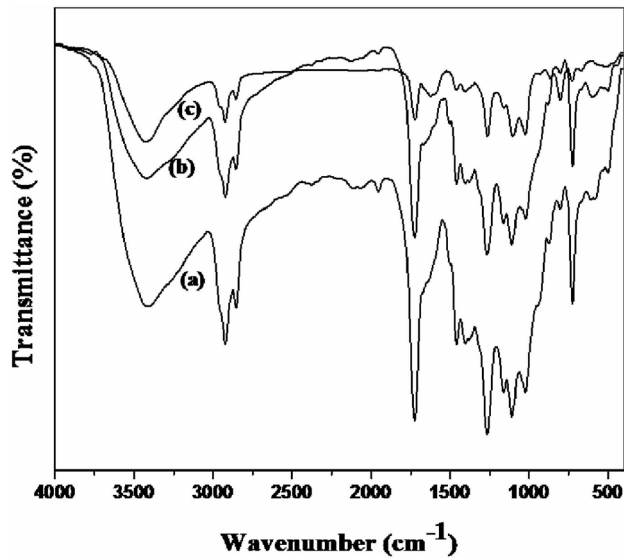


Fig. 6 FTIR spectra of (a) JT3 (b) JT3 after 60 days of soil burial degradation and (c) JT3 after 60 days of microbial degradation

As seen from these micrographs, the jute surface is covered with TPS resin (Fig. 7c) and after 60 days of degradation fibrous structure appeared on the composite surface (Fig. 7g). The smooth surface of JT3 composite changed into coarse as a result of debonding of resin from jute surface (marked by arrow) after biodegradation. SEM micrographs of JT4 before (Fig. 7d) and after soil burial (Fig. 7h), and those of JT3 and JT4 after 60 days microbial degradation is shown in Fig. 7i and j, respectively. It is found that the jute surface is completely roughened surface due to uncover of maximum thermoplastic starch after soil burial degradation of JT4 (Fig. 7h). This might be due to presence of

highest percentage of jute which allowed microbes preferentially degraded the most as compared to JT3. In case of microbial degradation, the whole composite surfaces (both JT3 and JT4) were found covered with fungus after 60 days (Fig. 7i and j) [23]. Optical analysis of jute and JT3 composite before and after 60 days of soil burial degradation are shown in Fig. 8. Figure 8b shows JT3 surface before degradation which is smooth, but after 60 days the surface topography changed, resin was uprooted in different places with full of grooves (marked by circle in Fig. 8d) observed. Plane surface of jute (Fig. 8a) was found degraded (marked by circle) and with fibrous structure (marked by arrow mark) in Fig. 8c after 60 days of degradation [10].

Both FT-IR and morphological analysis of composites surface revealed that the developed jute-TPS composites are degradable and have potential for an alternative to non-degradable composites. Being biodegradable in nature, the developed jute-starch composites can maintain fixed carbon mass in soil after end of their service periods.

Conclusions

Jute reinforced TPS composites with varying jute contents (10–40 wt.%) were prepared by use of any hazardous chemical solvent. Composite prepared with 30 wt.% jute felt showed the highest tensile strength of 27.3 MPa and flexural strength of 13.2 MPa, which is four times more than that of TPS. Water absorption of developed composites is low up to 11.2% due to presence of thermoplastic starch. Weight loss, FTIR, SEM and optical micrographs of composites after soil burial and microbial degradation revealed that composites are biodegradable in nature. Biodegradability and moderate hydrophobic nature are the prime advantages of these

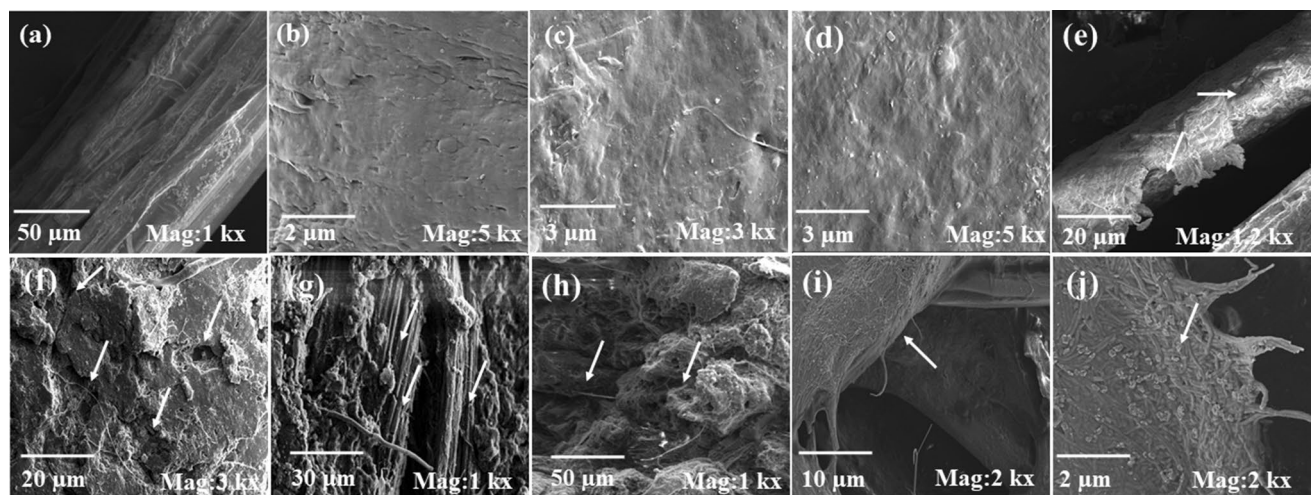
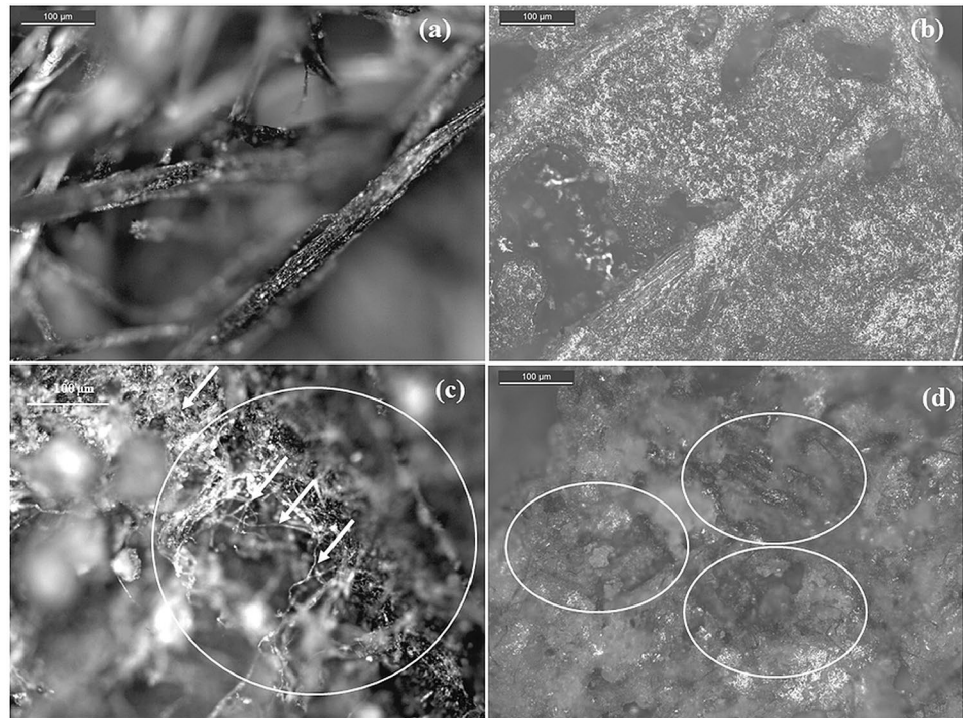


Fig. 7 SEM micrographs of (a) Jute, (b) TPS, (c) JT3, (d) JT4 and (e) Jute before degradation, (f) TPS, (g) JT3, (h) JT4 after 60 days of soil burial degradation, (i) JT3, (j) JT4 after 60 days of microbial degradation

Fig. 8 Optical micrographs of (a) jute, (b) JT3, and (c) Jute, (d) JT3 after 60 days of degradation



composites over other natural fiber reinforced composites. Starting from composite preparation to safe disposal, all the process is clean and eco-friendly and therefore possess great potential to be a part of green technology. As such, the developed composites may find end applications in various sectors including automobile, packaging units, indoor furnishing, toys and sporting goods and transportation.

Acknowledgements We gratefully acknowledge the financial support of Utkal University, Bhubaneswar as seed grant and DST-FIST programme to carry out some part of this work.

Compliance with Ethical Standards

Conflict of interest None.

References

1. Behera AK, Avancha S, Sen R, Adhikari B (2013) *J Appl Polym Sci* 127:4681
2. Torres FG, Arroyo OH, Gomez C (2007) *J Thermoplast Compos Mater* 20:207
3. Muller CM, Laurindo JB, Yamashita F (2009) *Carbohydr Polym* 77:293
4. Naik S, Shetty PB, Raghavendra S (2017) *Int J Mech Mater Sci Res* 7:1
5. Prachayawarakorn J, Sangnitidej P, Boonpasith P (2010) *Carbohydr Polym* 81:425
6. Curvelo AS, Carvalho AF, Agnelli JM (2001) *Carbohydr Polym* 45:183
7. Girones J, Lopez JP, Mutje P, Carvalho AF, Curvelo AS, Vilaseca F (2012) *Compos Sci Technol* 72:858
8. Fekete E, Kun D, Moczo J (2018) *Period Polytech Chem Eng* 62:129
9. Wang C, Li F, Wang L, Li J, Guo A, Zhang C, Liu P (2015) *RSC Adv* 5:49824
10. Behera AK, Avancha S, Basak RK, Sen R, Adhikari B (2012) *Carbohydr Polym* 88:329
11. Behera AK, Avancha S, Manna S, Sen R, Adhikari B (2014) *Polym Eng Sc* 54:345–354
12. Schlemmer D, Angelica R, Sales M (2010) *Compos Struct* 92:2066
13. Averous L, Digabel F (2006) *Carbohydr Polym* 66:480
14. Liu XY, Dai GC (2007) *Express Polym Lett* 1:299
15. Vilaseca F, Mendez JA, Pelach A, Llop M, Canigüeral N, Girones J, Turon X, Mutje P (2007) *Process Biochem* 42:329
16. Ufere SK, Sultana N (2016) *ARPJ Eng Appl Sci* 11:13686
17. Ahmed I, Niazi M, Hussain A, Jahan Z (2018) *Polym Plast Technol Eng* 57:17
18. Mello L, Mali S (2010) *Ind Crops Prod* 55:187
19. Gautam N, Kaur I (2013) *J Env Chem Eco* 5:147
20. Krasowska K, Heimowska A, Morawska M (2016) *E3S Web Conf* 10:48
21. Behera AK (2018) *IOP Conf Ser Mater Sci Eng* 410:1
22. Macedo JN, Rosa D (2016) *Key Eng Mater* 668:54
23. Zhao Q, Tao J, Yam RC, Mock AC, Li RK, Song C (2008) *Polym Degrad Stab* 93:1571

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.