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ORIGINAL ARTICLE

# From plant to product: investigation of a cellulosic fiber from *Xanthium strumarium* L. subsp. *strumarium* stem for its potential use in composite applications

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**Abstract**
In this study, cellulosic fibers obtained from the *Xanthium strumarium* L. subsp. *strumarium* (XSL) plant's stem were characterized. The aim of this study is to compare the characteristics of XSL fiber with different stem fibers such as flax, hemp, and jute that are commonly used in the composite industry for sustainability purposes. The XSL plant is abundant in nature and keeps growing throughout the year. Since it does not require too much water to grow, the XSL plant can be considered as both sustainable and environmentally friendly. No chemical process was used to obtain fiber from the plant; only water retting, which is a natural method, was applied. After the fiber extraction, morphological, thermal, chemical, and physical properties of the XSL fiber were investigated. Consequently, the XSL fiber's properties are determined as 49% cellulose content, 403 µm in average diameter, and as 1.57 g/cm$^3$ density. It was discovered through a single fiber strength test that the XSL fiber's mechanical characteristics make it appropriate to be used as a reinforcing fiber in composites. Additionally, thermal characterization revealed that the XSL fiber has a maximum decomposition temperature of 371.14 °C, indicating good thermal resistance. Characterization procedures concluded that XSL fiber can be an economic and environment-friendly reinforcement fiber alternative for composites.

**Keywords** *Xanthium strumarium* L. subsp. *strumarium* · Fiber characterization · Cellulose · Reinforcement · Composite

## 1 Introduction

*Xanthium strumarium* L. subsp. *strumarium* (XSL) is an annual plant that is native to America and Asia, and its stems and leaves can be used in various applications such as contemporary pharmacology [1–5] and conventional medical treatments [1, 4, 6–10]. The XSL plant can be used in different areas, such as medical procedures and medications. It is reported that it has long been used to treat skin conditions, and even cancer in traditional Chinese medicine [6] and has a promising potential for various treatment methods from traditional medicine to modern pharmacology [1, 3]. For instance, the XSL's uses in traditional Chinese medicine include treating headaches, ulcers, nasal issues, limb cramps, and numbness. Furthermore, many Native American tribes also utilized XSL as a remedy for vomiting, diarrhea, and constipation as well. The herb was used as an adulterant for *Datura stramonium*, and was thought to be useful in treating chronic malaria cases [2]. Chavan and Kulkarni discussed the morphology, medicinal qualities, and the phytochemical analyses of the XSL both to accurately identify and authenticate pharmaceuticals [5]. Experimental studies on mice have demonstrated that the XSL plant extracted caffeineic acid has blood sugar lowering (anti-hyperglycemic) effects [1]. Kamboj and Saluja [8] reported a comprehensive investigation of the XSL's botanical description, including the examination of its phytochemical components and its medicinal actions. Numerous other studies have identified compounds in this plant that possess bioactive features. Such compounds have been shown to exhibit antitumor, antibacterial, antifungal, antitussive, anti-inflammatory, antinociceptive, hypoglycemic, antimitotic, insecticidal, and antioxidant effects [4, 7–10]. Kaur et al. discussed the isolation and clarification of the chemical constituents from a petroleum ether extract

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of XSL leaves [2]. Here, the antioxidant and antibacterial capabilities of the isolated ingredients were also assessed. Fan et al. aimed to provide a comprehensive overview of the current literature of research on XSL, including its traditional uses, toxicology, pharmacology, pharmacokinetics, phytochemistry, and botany [4]. The plant seeds, which have the potential to yield oil, are also a significant source of biofuel [11, 12] with 25–45% crude oil [13]. The XSL plant's dense biomass, which forms a bushy structure, can be used to produce various building materials [14]. Moreover, it can prevent serious environmental damage like landslides, floods, and erosion, while helping the improvement of biodiversity [11–16].

As a weed, the XSL is not wanted in agricultural areas since it reduces the crop productivity by competing with other crops for resources, including water, minerals, light, and space. Additionally, it was reported that both the XSL roots and its above-ground leftovers cause developmental retardation in agricultural crop plants through an allelopathic effect [17]. In the literature, the harmful effects of the XSL plant consumption on the farm animals are also reported [8, 18].

The literature reveals that the majority of the as-conducted investigations on the XSL plant has focused on both the chemical composition and the pharmacological characteristics of its seeds [19, 20]. In contrast, the plant's roots, leaves, and stem have received comparatively less attention [4, 21, 22]. Thus, it is imperative that scientists carry out a thorough analysis of the XSL plant's other components to optimize the utilization of this plant [4, 22, 23]. Furthermore, the XSL plant's stem fiber characterization has not been reported yet.

Therefore, this study intends to perform the XSL plant's fiber characterization and to determine its possible utilization in composite production. These fibers' physical and mechanical properties were analyzed via scanning electron microscopy (SEM), thermogravimetric analysis (TGA), Fourier transform infrared (FTIR) spectroscopy, and X-ray diffraction (XRD) tests to unveil their structure. Although uses of the XSL plant's different parts for medicinal purposes have been explained in relevant previous studies, in the current study, it was tried to determine the possible use of this plant's stem fibers in composites field within the scope of sustainability. Thus, this can be considered as both the main contribution to the literature and the most novel aspect of this study. In addition, another novel aspect of this study is the determination of XSL stem fibers' alternative properties, via characterization, over other natural fibers in the literature that are used in composite materials' reinforcement.

## 2 Materials and methods

### 2.1 The XSL fiber extraction

The XSL stem fibers used in this study were obtained from different regions of the Adiyaman province in Turkey. During their procurement, XSL plants were carefully monitored to ensure they were not withered, and their fruits were ripe, as shown in Fig. 1a. As shown in Fig. 1b, the XSL plant stems were obtained after separating the unnecessary parts such as roots, leaves, and fruits. These stems were kept in a water-filled bucket for approximately 3 weeks as shown in Fig. 1c. Then, the stem fibers were extracted (Fig. 1d) by rinsing the stems that had been mainly rotten in the water.

### 2.2 Evaluation of fiber diameter and density

The density of XSL fibers was determined via the buoyancy (Archimedes) method in accordance with the ASTM D8171-18 standard [24]. This is test method B and it serves as a substitute for test method A in situations where less precise outcomes are acceptable. Archimedes' principle is the statement that a substance's buoyant force is equal to the weight of the fluid that the object has displaced. The average diameter of XSL fibers was measured by using SEM.

### 2.3 Chemical composition quantification

The cellulose, hemicellulose, lignin, wax, and moisture compounds that comprise the fundamental structure of XSL fibers were identified. For that, the XSL fiber samples were crushed into a powder form, and then dried at 100 °C in an oven for 4 h before their chemical analysis, which was performed as described in Mylsamy and Rajendran's study [25].

### 2.4 Classification of XSL fiber's chemical functional groups

FTIR spectra of the XSL fibers were acquired by using a PerkinElmer Spectrum BX FTIR spectrometer within a wave number range from 4000 to 400 $cm^{-1}$, and with a scan rate of 32 scan/min and a signal-to-noise ratio resolution of 2 $cm^{-1}$.

### 2.5 Crystallinity index determination

The XSL fibers' crystallinity index was calculated depending on the reflection from the XRD patterns. Here, the fibers were powdered, and to remove any moisture, they were dried in an oven before starting the measurement process. The XRD patterns of the fibers were recorded by using a Rigaku Miniflex600 diffractometer at a scan rate of 0.75°/

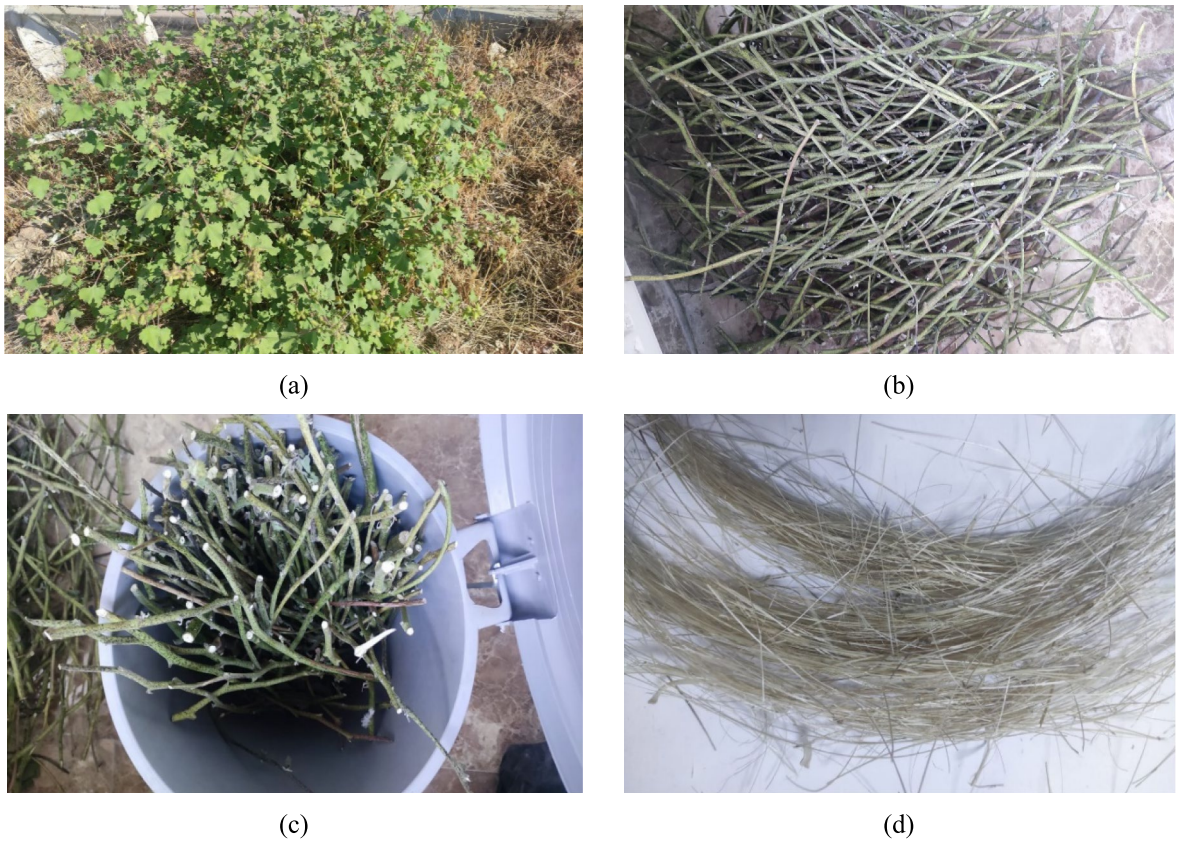



**Fig. 1** The XSL plant in a vegetative state (**a**), XSL stems prepared by removing its leaves and roots (**b**), XSL stems in the bucket that is ready-to-decompose to extract its fibers (**c**), and the extracted XSL stem fibers (**d**)

min, at a step speed of 0.02°, and at a wavelength of 1.540 (λ) between 5 and 55°. Therefore, the total duration of the test was 67 min. An X-ray photoelectron spectroscopy (XPS) with 250-µm beam diameter and with an X-ray source of monochromatic Al-Ka device (1486.7 eV) was used to quantify the XSL fibers' atomic concentration. At 200 eV of pass energy and 1 eV of precision, the XPS data was collected within the range of 1361–10 eV. Before the XSL fiber samples' surface investigation, ionic Ar gas was sputtered, and 20 scans were made on a single location to gather the XRD data.

In this study, the background-corrected Segal peak height method was employed to determine the XSL fiber samples' crystallinity value [26]. In this method, the environmental scatter, such as shot noise, sample holder, and the air scatter, makes up the "broad background." Here, first, the XRD device ran empty, which is known as the "blank run" in the XRD graph, and the relevant values were obtained. Next, the XSL fibers' XRD values were obtained. From these runs, the XSL fibers' both $I_{200}$ and $I_{am}$ parameters, used in the Segal equation, were obtained simply by subtracting the XSL fibers' values from the background XRD values. Eventually, the as-obtained values were utilized in the Segal equation, and the crystallinity index (CI) was calculated as shown in Eq. 1 below.

$$\mathrm{CI}\,(\%) = \frac{I_{200} - I_{\mathrm{am}}}{I_{200}} \times 100 \tag{1}$$

Here, $I_{am}$ is attributed to the 2θ angle ~ 18.5° that is between two peaks near 15.5° and 22°, which are attributed to the overlapped peaks of $(1\bar{1}0/110)$ and the (200) peak, respectively. According to the Segal CI equation, the maximum intensity value is observed at 2θ angle ~ 22° [27].

## 2.6 Thermal degradation behavior analysis

To evaluate the thermal stability of XSL fiber samples, a Seiko SII TG/DTA 7200 device was used. To perform the analyses, 10 °C/min heating rate was applied to 5 mg fiber specimens in $N_2$ atmosphere from 30 to 700 °C.

## 2.7 Examination of surface morphology

By using a ZEISS/EVO LS10 brand SEM with a high-resolution test apparatus, the XSL fibers'

morphological structure, diameter, and surface porosity were characterized.

### 2.8 Tensile property measurement

The XSL fibers that are 10 mm in length were tested on an Instron Universal Tester with a 50 N load cell, and at a speed of 0.1 mm/min as per ASTM D3822-07 standard [28]. Fibers were put through 30 iterative tensile tests to determine their microfibril angle ($\alpha$) by following Eq. (2) as shown below.

$$\varepsilon = \ln\left(1 + \frac{\Delta L}{L_0}\right) = -\ln(cos\alpha) \quad (2)$$

In this equation, $\Delta L$ is the elongation at break (mm), $L_0$ is the gauge length (mm), $\alpha$ is the microfibril angle in degrees, and $\varepsilon$ is the deformation or strain [29, 30].

## 3 Results and discussion

### 3.1 The XSL fiber's physical characteristics

The density of XSL fiber was calculated as 1.57 g/cm$^3$, and its comparison with other natural fibers is given in Table 1.

It can be observed from Table 1 that the XSL fiber has a higher density compared to all other commonly used natural fibers in the relevant literature. Additionally, its fiber diameter has a wide range between 362.81 and 445.15 µm, indicating a promising potential as a good reinforcing material alternative in composite structures, as can be seen in Table 1.

**Table 1** The as-reported natural fibers' density comparison with the XSL fiber

| Natural fiber | Density (g/cm$^3$) | Diameter (µm) | Ref |
|---|---|---|---|
| *Xanthium strumarium* L. subsp. *strumarium* | 1.57 | 403.98 ± 41.17 | This study |
| Hemp | 1.48 | 26 | [31] |
| Cotton | 1.53 | 8–20 | [31] |
| Kenaf | 1.45 | 34.2–43.2 | [32] |
| *Cissus quadrangularis* root | 1.5 | 610–725 | [33] |
| *Coccinia grandis* stem | 1.51 | 543–621 | [34] |
| Sisal | 1.45 | 121.6–411 | [35] |
| Flax | 1.5 | 5–38 | [36] |
| Jute | 1.46 | 5–25 | [36] |
| Hemp | 1.5 | 10–51 | [36] |
| *Ageratina adenophora* | 1.32 | 148.34–165.58 | [37] |
| *Abutilon indicum* | 1.17 | 175 | [38] |
| Lavender | 0.87 | 295 | [39] |
| *Ficus benjamina* L | 0.86 | 331.95 ± 23 | [40] |
| *Tithonia diversifolia* | | 56.09–76.02 | [41] |
| *Cyperus papyrus* | 0.95–1.15 | 22.32–32.37 | [42] |
| *Cyperus platystylis* R.Br | | 22.20–28.00 | [43] |
| Reddish shell bean | 1.08 | 785.87 | [44] |
| *Nicotiana rustica* L | 1.5 | 36.88 ± 10.54 | [45] |
| *Platanus orientalis* L | 1.36 | 181.01 ± 9.81 | [46] |

### 3.2 The XSL fiber's chemical properties

Table 2 shows the XSL and other natural fibers' chemical compositions. The general composition of cellulose-based natural fibers consists of lignin, hemicellulose, cellulose, and other components. Here, one of the most important chemical compounds of these fibers is cellulose, and its proportion in the fiber's chemical structure directly affects the relevant composite's mechanical property that is reinforced with the fiber [38].

It can be observed from Table 2 that the XSL fiber extracted from the plant's stem has either higher or lower cellulose content than other relevant fibers reported in the studies examining the cellulosic-based natural fibers' properties. It is commonly stated in such studies that the composites produced by utilizing a high cellulose content fiber obviously have improved mechanical properties.

On the contrary, it was observed that the hemicellulose content in a fiber negatively affected the overall mechanical properties. Here, the XSL fiber seems to have a lower hemicellulose content (10.4%) compared to many other relevant fibers reported in the literature.

With a hydrophobic structure, lignin has an impact on a fiber's surface structure, and its moisture absorption capacity, as well as its protection against harmful external effects (fungi and bacteria) that the fiber is exposed to [57]. Here, the XSL fiber's moisture content was determined as low as 6.98% due to its high lignin content. However, it was reported in the literature that a fiber's level of moisture absorption has a potential negative impact on its reinforcement property in composites due to limiting the fiber/matrix interfacial compatibility [38]. Thus, the XSL fiber with a low moisture content can be considered to have a promising potential to be used as a fibrous reinforcing agent in a composite structure.

## 4 The XSL fiber's XRD analysis

The XSL fiber's XRD graphic is given in Fig. 2. Here, the cellulose I peak that arises from the overlapped small crystallites in (1 $\bar{1}$ 0/1 1 0) planes, is located at 15.76° [58–61]. The cellulose I peak at 22.20° corresponds to the (2 0

**Table 2** The XSL and other natural fibers' chemical compositions

| Natural fiber | Chemical components | | | | Ref |
|---|---|---|---|---|---|
| | Cellulose (wt%) | Hemicellulose (wt%) | Lignin (wt%) | Moisture content (wt%) | |
| *Xanthium strumarium* L. subsp. *strumarium* | 49 | 10.4 | 27.5 | 6.98 | This study |
| *Chrysanthemum morifolium* | 32.9 | 13.8 | - | - | [47] |
| *Conium maculatum* | 49.5 | 32.2 | 8.6 | - | [48] |
| *Muntingia calabura* bark fiber | 41.5 | 11.3 | 7.6 | 6.1 | [49] |
| *Agave americana* | 68.4 | 18.6 | 4.85 | - | [25] |
| *Glycyrrhiza glabra* | 40.46 | 15.94 | 12 | 9.93 | [50] |
| *Catharanthus roseus* | 47.3 | 9.1 | 15.1 | 8.3 | [51] |
| Kenaf | 45–57 | 8–13 | 21.5 | 6–12 | [52] |
| *Calotropis procera* | 54.5 | 12.3 | 14.8 | 9.3 | [53] |
| *Tridax procumbens* | 32 | 6.8 | 3.0 | 11.2 | [54] |
| *Parthenium hysterophorus* | 51.5 | 4.3 | 9.7 | 8.6 | [55] |
| *Abutilon indicum* | 56.12 | 14.26 | 16.21 | 16.21 | [38] |
| *Tithonia diversifolia* | 65.33 | 12.25 | 15.06 | 9.23 | [41] |
| *Jatropha integerrima* | 75.3 | 7.84 | 7.61 | 5.12 | [56] |
| *Cyperus papyrus* | 61.82 | 11.82 | 23.6 | 9.86–11.09 | [42] |
| *Cyperus platystylis* R.Br | 66.1 | 20.12 | 13.28 | - | [43] |
| *Nicotiana rustica* L | 56.6 | 11.8 | 14.97 | 13.15 | [44] |
| *Platanus orientalis* L | 42.03 | 13.5 | 28.35 | 10.86 | [46] |
| Flax | 61.4–71 | 18.6–20.6 | 2–5 | 7 | [36] |
| Hemp | 68–72 | 7–15 | 4–6 | 8 | [36] |
| Jute | 61 | 13.6–24 | 12–25 | 12.1 | [36] |

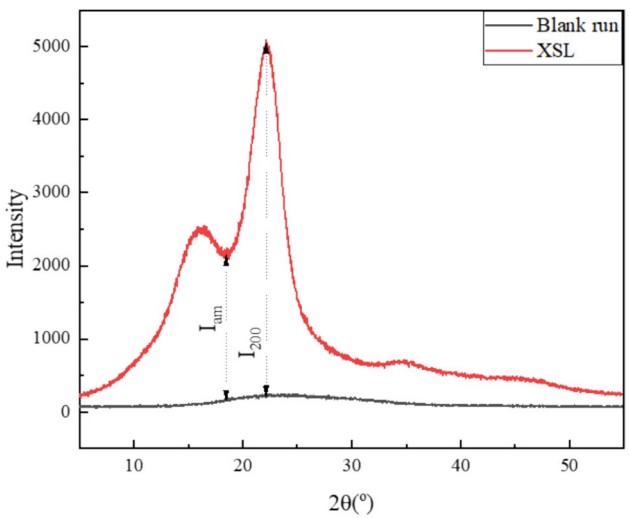



**Fig. 2** The XSL fiber's XRD graphic

0) plane [58, 62]. Additionally, the (0 0 4) plane can be attributed to a weak peak at 34.74° [61]. $I_{am}$ was obtained at 2θ = 18.48°. Through Eq. 1, the XSL fiber's CI value was calculated as 61.01%, which is higher than that of other vegetable fibers reported in the literature [49, 51, 54, 63, 64]. The XSL fibers' tensile properties are enhanced by their high crystallinity, indicating their more regularly aligned cellulose chains [47].

### 4.1 The XSL fiber's FTIR analysis

The XSL fiber's FTIR spectrum in Fig. 3 provides qualitative information about its chemical structure. Here, the -OH bond, indicated by a broad peak located at 3353 $cm^{-1}$, is associated with cellulose. According to Oh et al. and Khan et al., the peak at 2908 $cm^{-1}$ is associated with the C-H bond in cellulose and hemicellulose that are present in XSL fibers [61, 64]. Either the presence of lignin or the C = O vibration in hemicellulose's ester group can be the possible causes of the peak located at 1730 $cm^{-1}$ [65]. The peaks located between 1452 and 1231 $cm^{-1}$ correspond to both lignin and the fiber's capacity to absorb moisture [38, 65]. Located at 1028 $cm^{-1}$, the sharp peak is associated with C-O or O–H groups [66], and according to Mwaikambo and Ansell, the small peak located at 830 $cm^{-1}$ is an indicative of β-glycosidic bonds between monosaccharides [67].

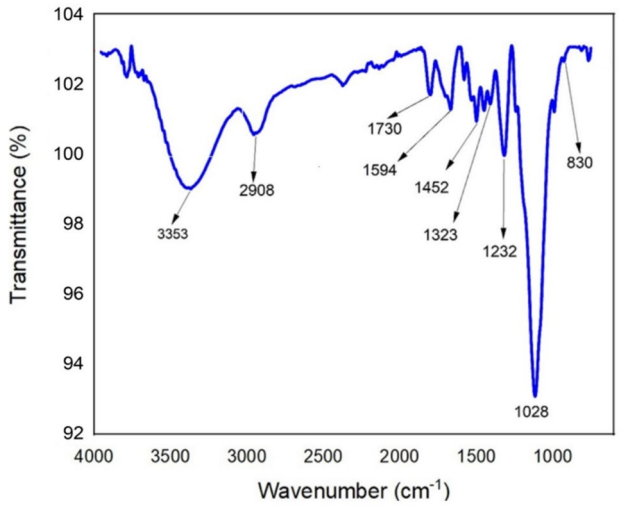



**Fig. 3** The FTIR spectrum of the XSL fiber

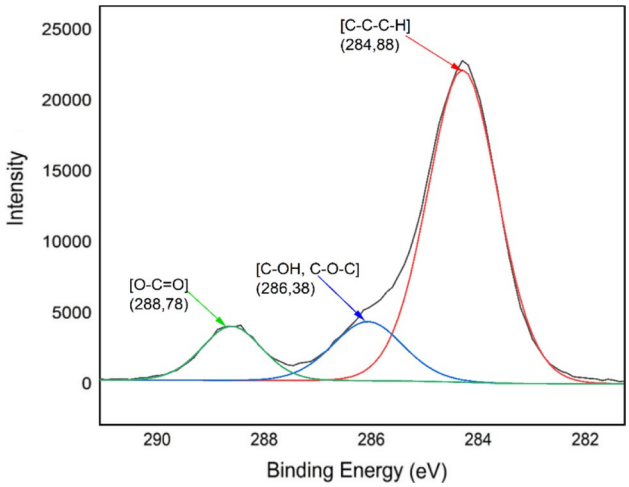



**Fig. 4** The XSL fiber's (C1s) XPS spectra

## 4.2 The XSL fiber's XPS analysis

The constituent elements present on the XSL fiber's surface is shown in Table 3. Based on the elemental analysis, there is 68.43% carbon, 17.34% oxygen, 1.61% nitrogen, and 1.48% silicium detected on the fiber surface.

Here, the presence of silicium and nitrogen-like atoms in the fiber structure can be attributed to the environmental conditions in which the fiber is grown and harvested [57]. Based on the results shown in Table 3, the oxygen to carbon ratio, which determines the fiber surface's hydrophilic characteristics, in XSL fibers was calculated as 0.25, and it is lower than that of jute (0.46) [68], kenaf (0.45) [48, 69], and hemp (0.27) fibers [47]. It can be ascertained by its low carbon to oxygen ratio that the XSL fibers' surface hydrophilicity is lower than other cellulosic fibers commonly used in composites [48, 68–71]. Since natural fibers are hydrophilic, they adhere to the hydrophobic matrices weakly, which has a negative impact on their mechanical properties, as well as their processability as stated by Karimah et al. [71]. The XSL fiber's carbon (C1s) spectra curves are given in Fig. 4.

Here, the [C–C-C-H] bonds from hemicellulose and lignin are indicated by a big sharp peak at 284.88 eV [48, 57, 72], and the [C–OH, C–O–C] bonds are indicated by a small wider peak at 286.48 eV [48, 57, 72, 73], while the [O-C = O] bonds originating from lignin are represented by another small peak at 288.88 eV [57, 72].

**Table 3** Surface atomic components of the XSL fiber

| | C1s (%) | O1s (%) | N1s (%) | Si2p (%) |
|---|---|---|---|---|
| *Xanthium strumarium* L | 68.43 | 17.34 | 1.61 | 1.48 |

## 4.3 The XSL fiber's SEM analysis

In cellulosic fiber–reinforced composites, determining the fiber morphology is an important factor for the fiber/polymer interface compatibility since it majorly affects the composite material's life span. Therefore, determining the reinforcing fibers' surface morphology is essential.

The XSL fiber's both axial and cross-sectional images were taken at 100×, 300×, and 1000× magnifications by using SEM, and they are shown in Fig. 5.

A rough surface covered with impurities without on the fiber's exterior, a specific geometry was noticed. Untreated fibers show a multicellular structure consisting of lignin, impurities, hemicellulose, and cellulose. The particles in Fig. 5a were estimated to belong to hemicellulose [74]. Various surface modifications can remove these impurities on the fiber surface to increase compatibility with matrices. It was determined that the cross-section consists of microfibrils resembling hexagonal and cylindrical geometry. In addition, with its rough surface structure, it can positively impact the composite's characteristics by creating a good fit along the interface of the fiber and matrix [57, 74].

Additionally, it was determined that the XSL fiber's microfibril angle was $16.26 \pm 2.84$ with respect to Eq. 2. For the fibers of jute, flax, hemp, *Brassica oleracea* var. *botrytis* L., and *Cissus quadrangularis*, 8.1°, 5°, 6.2°, 19.53°, and 4.95°, respectively, are the reported microfibril angles [29, 30]. As per Indran and Raj [29], a lower microfibril angle results in improved mechanical properties. Therefore, it is possible to state up to a certain point that the XSL fiber has better mechanical properties than *Brassica oleracea* var. *botrytis* L. fiber whereas poorer properties according to jute, flax, hemp, and *Cissus quadrangularis* fibers [29, 30].

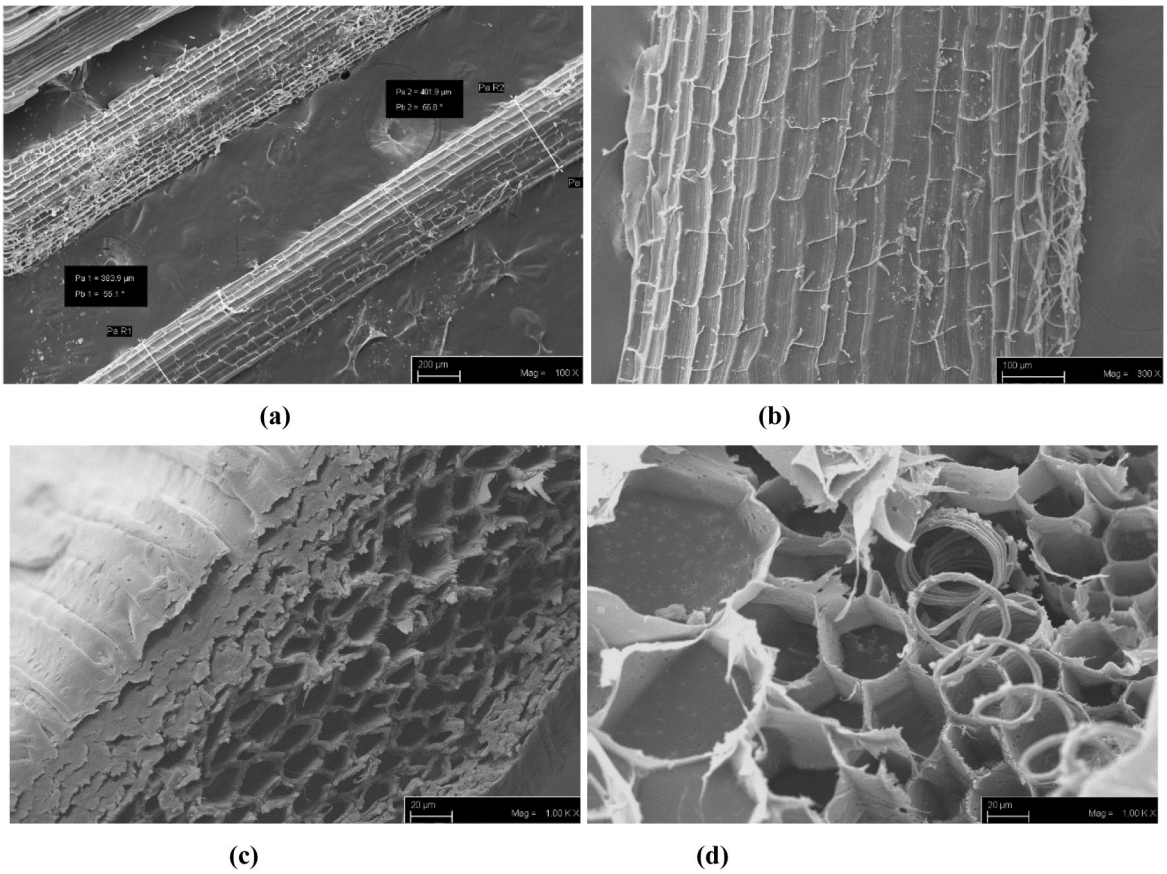



**Fig. 5** The XSL fiber's axial (**a**, **c**) and cross-sectional (**b**, **d**) SEM images at different magnifications

### 4.4 The XSL fiber's thermal analysis

The fiber's thermal stability can be obtained by combining the peak temperatures from DTG and DTA with the degree of decomposition and residual weight from TGA to comprehend the thermal character of the fiber. While DTA sheds light on the endothermic or exothermic degradation processes, TGA and DTG together show the phases and rate of degradation. Since thermal resistance is a critical component in a variety of industries, it is imperative to comprehend the thermal stability and degradation behavior of natural fibers [75, 76]. The XSL fiber's TG/DTG thermogram curve is given in Fig. 6. Here, there was 7.08% weight loss that occurred between 30 and 100 °C due to moisture evaporation that is present in fibers' structure [77]. Between 200 and 375 °C, there was a total of 64.42% weight loss that occurred, in which the first small inclination with a shoulder at 286.02 °C accounts for the degradation of hemicellulose, lignin, and glycosidic linkages in cellulose [75, 76], while the second deeper inclination shows the section during which the cellulosic part of the XSL fiber started to deteriorate [78]. The amount of XSL fibers' residue after this thermal degradation section was 15.7%.

Here, the peak at 371.14 °C illustrates the highest temperature at which the XSL fibers' cellulosic structure thermally broke down. This temperature is similar to the findings of Seki et al. as 381.0 °C for *Luffa cylindrica* [79], *Coccinia grandis* L. (351.6 °C) [80], *Dichrostachys cinerea* (359.3 °C) [81], and 362.4 °C for *Acacia planifrons* [82]. It is understood from these results that with a thermal degradation temperature of 286.02 °C, the XSL fiber has the potential as a reinforcing agent in composite production [83–85].

### 4.5 The XSL single fiber's mechanical property analysis

Natural fibers, made up of cellulosic material, have different characteristics that are majorly affected by their chemical structure, environmental growing conditions, and fiber obtaining and analysis methods leading to different mechanical properties. The comparison of a single XSL fiber's mechanical properties to other relevant fibers are given in Table 4.

Based on the mechanical property comparison results, the XSL fiber is observed to have a higher average tensile strength of 149 MPa, and similarly it has a higher average

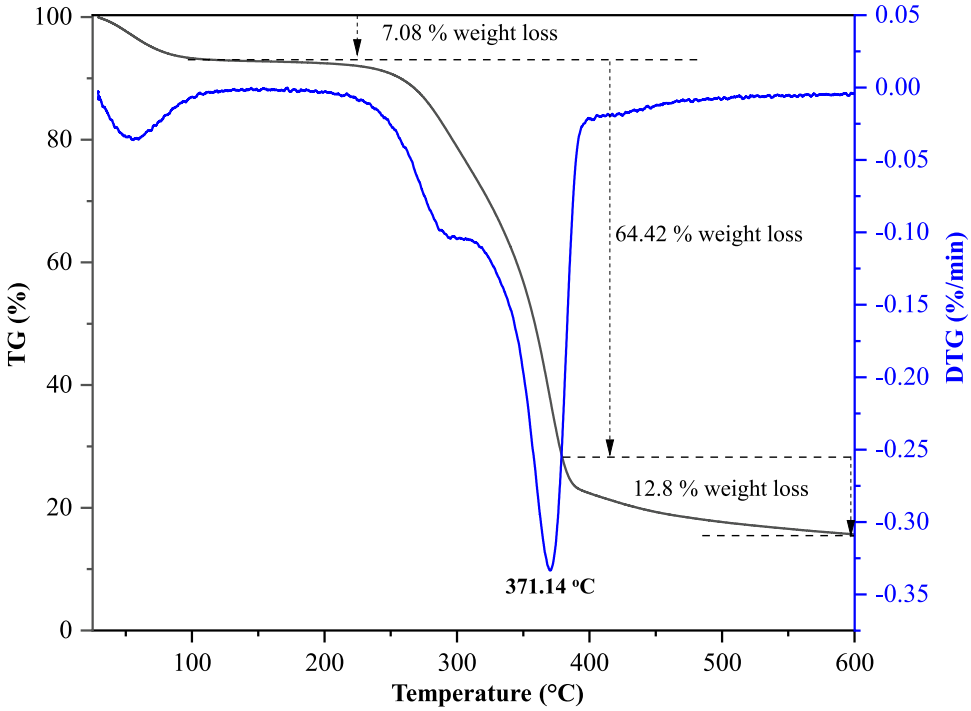



**Fig. 6** The XSL fiber's TG/DTG graphic

tensile modulus of 5.74 GPa than all the other stem fibers except flax, jute, and napier grass, respectively. In addition, its elongation at break is 3.91%, which is quite competitive according to Table 4. Thus, it can be concluded that the XSL fiber has a promising potential as an alternative reinforcement fiber to be used in composites.

## 5 Conclusions

In this study, both characterization and application potential evaluation of a cellulosic fiber extracted from the XSL plant's stem as a reinforcing agent in composites was investigated. The fiber's physical investigation revealed that it has the density of 1.57 g/cm$^3$, which is similar to other types of natural fibers that are commonly used in composite material production.

The XSL fiber's major chemical components like cellulose and hemicellulose were determined by FTIR analysis.

**Table 4** The comparison of XSL fiber's mechanical properties to other cellulosic fibers

| Natural fiber | Mechanical properties | | | |
|---|---|---|---|---|
| | Tensile strength (MPa) | Tensile modulus (GPa) | Elongation at break (%) | Reference |
| *Xanthium strumarium* L. subsp. *strumarium* | 149 ± 3.91 | 5.74 ± 0.38 | 3.91 ± 0.45 | This study |
| *Catharanthus roseus* | 27.02 ± 1.10 | 1.23 ± 0.04 | 2.15 ± 0.1 | [51] |
| Banyan tree root | 19.37 ± 7.72 | 1.8 ± 0.40 | 1.8 ± 0.40 | [83] |
| Coconut tree leaf sheath | 46.4 | 2.3 | 2.84 | [29] |
| *Glycyrrhiza glabra* | 132.40 ± 31.21 | 4.47 ± 0.93 | 4.48 ± 0.87 | [50] |
| Flax | 500–1500 | 27 | 2.7 | [29] |
| Hemp | 270–705 | 20–70 | - | [36] |
| Jute | 393–773 | 26 | 1.5–1.8 | [29] |
| Napier grass | 88.4 | 13.1 | 0.99 | [86] |
| *Grewia tilifolia* | 65.2 | 65.2 | 65.2 | [87] |
| *Tridax procumbens* | 25.75 | 0.94 ± 0.09 | 2.77 ± 0.27 | [54] |

It was revealed by a chemical analysis that with its 49% cellulose, 10.4% hemicellulose, and 27.5% lignin ratios, this fiber can enhance a composite's mechanical properties when used as a reinforcing agent. The XSL fiber was observed to have 61.01% CI value based on its XRD data. Additionally, the XSL fiber was observed to have competitive mechanical properties like Young's modulus, tensile strength, and % elongation compared to other cellulosic fibers. It was also measured that the average tensile strength of XSL fibers is 149 MPa.

The XSL fiber's TGA revealed that it has high thermal stability with initial and maximum decomposition temperatures of 286 °C and 371 °C, respectively. Also, with an O/C ratio of 0.25, the XSL fibers exhibit good hydrophobic properties, as determined by their surficial chemical components' XPS analysis.

Finally, the XSL fibers' SEM analysis revealed that their surface is both rough and composed of impurities. It was determined that their fiber/matrix interface compatibility can be improved by a surface modification. After thorough characterizations, it was concluded that the XSL fibers have promising potential to be an alternative reinforcing fiber for composites.

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**Data availability** Upon reasonable request, the corresponding author will make the datasets available.

## Declarations

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

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