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ORIGINAL ARTICLE

Extraction and characterization of novel cellulosic fiber from *Phytolacca americana* plant stem

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Abstract
In this study, a novel cellulosic plant-based fiber was extracted from *Phytolacca americana* (inkberry) as a sustainable substitute natural fiber for synthetic fibers. For this purpose, an extended characterization of inkberry fibers was carried out. The elemental composition was determined as 58.27% carbon and 41.70% oxygen. Moreover, an image processing approach was presented and used for computing the average thickness of cellulosic inkberry stem fiber. Fiber diameter was estimated from the scanning electron microscope micrographs with image processing as 480.56 µm. The scanning electron microscope image indicated that inkberry fiber has a smooth surface with a channel structure. X-ray diffraction analysis revealed that the fiber has a 4 nm crystalline size with a 51.4% crystalline index. Fiber functional groups were characterized with Fourier transform infrared analysis. The mechanical behaviors of inkberry fiber were tested with a single fiber tensile test device, and tensile strength was determined as 146.5 MPa, Young's modulus was found as 24.8 GPa, and elongation at break of fiber was obtained as 2.37%, respectively. Furthermore, the fiber was thermally stabilized up to 435.37 °C with thermogravimetric analysis. These physico-chemical behaviors confirm that inkberry fiber may be recognized as a promising reinforcement fiber in polymer matrix composites for many non-structural applications, which are interior body panels in yachts, automobiles, partition boards in buildings, and barriers.

Keywords *Phytolacca americana* · Cellulose · X-ray diffraction · Tensile strength · Thermal-gravimetric analysis · Image processing

1 Introduction

In recent times, there has been an important trend in search relevance in cellulosic-based fiber composites, driven by a raised awareness of ecological issues and an urgent need to identify sustainable substitutes to synthetic fiber-reinforced composites. Conventional synthetic fibers, which are aramid, carbon, nylon, and glass, have commonly been utilized as reinforcement in polymer composites despite their non-biodegradability and adverse environmental impacts. As a consequence, the discovery of new cellulosic fibers as a potential substitute for synthetic fibers has gathered speed due to their brilliant characteristics, involving low density, cost-effectiveness, ready availability, resistance to corrosion, eco-friendliness, and biodegradability [1–5].

In recent years, many researchers have focused on synthesizing novel materials using natural substances [6–9]. Cellulosic natural fibers may be obtained from different sources like climbers, herbs, vines, grasses, trees, and shrubs. These fibers are commonly specified from the plant bodies which are stem, flower, root, seeds, fruits, stalks, petioles, and barks. The architecture of cellulosic fibers involves cellulose, lignin, hemicellulose, ash, wax, and traces of another soluble substitute. Chemical, mechanical,

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and physical behaviors of cellulosic fibers vary from each other owing to many factors, which are maturity, chemical composition, cultivation region, quantity of soil micronutrients, environmental conditions, and part of the plant where the fiber is obtained. New natural fibers are beginning to appear as a result of the growing gap between the market need and the rate at which conventional fibers like banana, cotton, hemp, flax, and jute are being grown [10]. The recent new cellulosic natural fibers are *Tabernaemontana divaricate* [1], reddish shell bean [11], *Sambucus ebulus* L. [12], *Leucaena leucocephala* tree [13], *Syagrus romanzoffiana* rachis [13], *Jatropha integerrima* [14], *Ageratina adenophora* [15], *Abutilon indicum* [16], *Ficus benjamina* L. [17], etc.

Eyupoglu et al. investigated the characteristic properties of the original cellulosic fiber from the *Sambucus ebulus* L. plant stem. Results indicate that the fiber has a high thermal stability of 456.98 °C and may be chosen in polymer composite materials for superior temperature applications [8]. In a different study, new cellulosic fiber was obtained from aerial roots of the banyan tree. Higher values of the crystallinity index, such as 72.47%, are typically found in banyan tree fibers, indicating higher crystalline cellulose and contents in nature [18]. Bhunia et al. searched for an original plant-based fiber gained from a *Cyperus compactus* plant stem. The results show that the fiber is included in a high quantity of cellulose (67.9%), perfect tensile strength (943 MPa), and high thermal stability (227 °C) [19]. Ferfari et al. extracted novel cellulosic fiber from *Syagrus romanzoffiana.* The crystallinity index of fiber figured out as 40.81%, and the fiber is stable up to 352 °C temperature. Tensile strength, Young's modulus, and elongation at break of fiber were determined as 671 MPa, 415 GPa, and 1.84% [19]. Another study reported the obtained new cellulosic fiber from *Yucca treculeana* (*YT*), which was defined as a potential reinforcement material. The crystalline size and crystallinity index were detected as 3.02 nm and 48.85%. The fiber has higher cellulose content (82.3%) and maximum temperature stability (360.6 °C) [20]. Researchers extracted cellulosic fiber from *Ziziphus jujuba.* The cellulose content of the fiber was determined as 43%, the crystallinity index was estimated as 35.70%, and the fibers were stable up to 335 °C [21]. Sarala carried out the characterization of *Derris scandens* stem fibers. The chemical analysis results showed that the fiber has 63.3wt% cellulose, 11.6wt% hemicellulose, and 15.3wt% lignin. The crystallinity size and crystallinity index of fiber were estimated as 11.92 nm and 58.15%, respectively. Single fiber tensile strength test demonstrated that the fibers displayed 633.87 MPa tensile strength and 13.54 GPa Young's modulus [5]. Bhunia et al. extracted new stem fiber from *Cyperus platystylis* R. Chemical constituent analysis and X-ray diffraction revealed that the fibers have a 41.12% crystallinity index and 66.1wt.% cellulose. The mean diameter and length of fiber were estimated as 23.36 μm. The tensile strength was determined as 657 MPa for 50 mm fiber length, and Young's modulus was calculated as 88.76 MPa [22]. Hadou et al. characterized and extracted a new cellulosic fiber from *Dracaena draco* plant. The findings prove that linear density, average density, moisture content, and moisture recovery are 18.87 Tex, 1.2043 g/cm^3, 11.54%, and 12.88%, respectively. X-ray diffraction reveals a crystallinity index of 30.42% and a crystallinity size of 3.14 nm. Thermogravimetric analysis shows that the fiber constant is at a temperature of 329.5 °C. The mechanical tests indicate that the fiber has 553 MPa strength, 2.5% elongation at break, and 24.9 GPa Young's modulus [23].

Phytolacca americana is a perennial herb with a large white inkberry that can usually grow up to 2 to 3 m. The petiole is 1–6 cm long, and the stems are red or green. The plant is native to North and Central America, but it grows in nearly all the world. In Turkey, the *Phytolacca americana* plant is cultivated in the Black Sea and Mediterranean regions on the sides of streams, timberlines, and roadsides. In addition, this plant is commonly found in Turkey, and no special conditions are required to grow this plant. The plant flowers between June and September. It is used in alternative medicine owing to relieving a variety of ailments, mostly used to treat inflammatory conditions and obesity with the obtain of different parts of the plant [24, 25].

There is no research in the literature on the properties and uses of *Phytolacca americana* (inkberry) plant stem fiber, and more studies are needed in this field, especially in terms of its potential benefits in industrial applications. The primary objective and contribution of this paper is to gain an unused cellulosic fiber from the stem of inkberry plant owing to physico-chemical and mechanical identification. For this purpose, it is aimed to bring a novel cellulosic fiber to humanity. To the best of the authors' knowledge, obtained and characterization of novel cellulosic fiber from the stem of inkberry plant is not reported in the literature. For these aims, morphological, mechanical, and physico-chemical properties of inkberry plant fiber were characterized with scanning electron microscope (SEM), image processing, single fiber tensile strength test device, X-ray analysis (EDX), Fourier transform infrared (FT-IR), X-ray diffraction (XRD), and thermal gravimetric analysis (TGA). Fiber average thickness was computed with the image process. Consequently, the results were checked against some other new plant-based fibers. Furthermore, inkberry fibers may be utilized productively for polymer matrix composites with usefulness in the environment, cost, and society as an alternative to man-made fibers.

2 Material and method

2.1 Inkberry stem fiber

Inkberry stem fiber was acquired from inkberry plants harvested in June 2022 in Bolu-Turkey (Black Sea Region). In literature, obtained and characterization of novel cellulosic fiber from the stem of inkberry plant is not reported. The fibers were extracted with the biological degradation method from the stem of the plant. Firstly, the stems were collected and separated from leaves and fruits. After, the stems were plunged in distilled water for 4 weeks in room conditions. After the biological degradation of the stems, the fibers were separated by hand; the obtained fibers were washed with running water at room conditions and left to remove moisture in direct sunlight for a week. Inkberry stem fiber obtained process is given in Fig. 1.

2.2 Density of fibers

The density of inkberry stem fiber was assigned with Archimedes Law according to ASTM D8171-18 standard and computed with Eq. 1:

$$d = \frac{W_d}{W_d - W_s} \tag{1}$$

In this equation, d accounts for the density (g/cm^3), W_d represents the dry weight, and W_s symbolizes the effective mass of fiber submerged in distilled water [26].

2.3 Scanning electron microscopy

The inkberry fiber samples were monitored with a FEG250 scanning electron microscopy (FEI QUANTA model) (FEI Company, Oregon, USA) under high vacuum with 1000 × and 250 × magnification at 5 kV.

2.4 Image processing-based computation of average thickness of inkberry stem fiber

The average inkberry stem fiber thickness was assessed using a new image processing-based approach. Figure 2 shows the steps of the presented approach.

The flowchart indicates that the initial step is to read the SEM image of inkberry stem fiber in the longitudinal direction. The second step is to convert the fiber image in RGB format to grayscale. Next, the Sobel filter is applied to identify the fiber edges. In the sequel, the noises are removed from the fiber image, the gaps are filled, and the fiber region in the image is found. The numbers of thickness pixels are then calculated vertically until the calculation is complete across the entire fiber region. After, the thickness pixel numbers are prorated with the SEM reference measurement result, and the real thickness values are attained. As the final step, the average thickness of inkberry stem fiber is computed, and a histogram graph is plotted.

2.5 Energy dispersive X-ray analysis

Elemental analysis of inkberry stem fiber was achieved with energy dispersive X-ray analysis by using FEI QUANTA X-ray spectroscopy (FEG 250 model) (FEI Company, Oregon, USA). Before the analysis, the samples were encompassed with gold–palladium (Au-Pl).

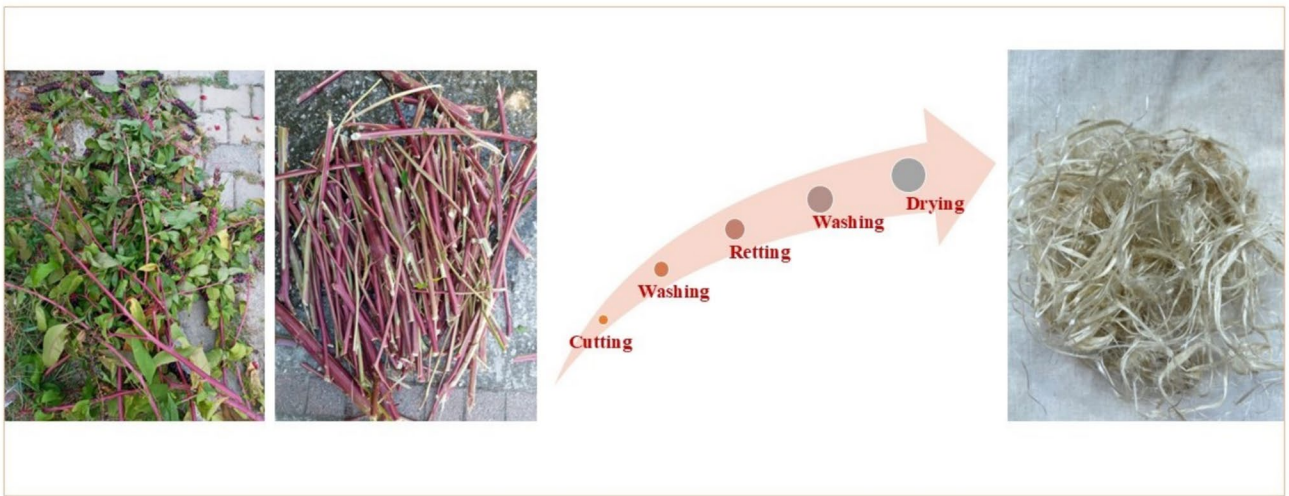

Fig. 1 Inkberry plant, inkberry stem fiber, and obtained process

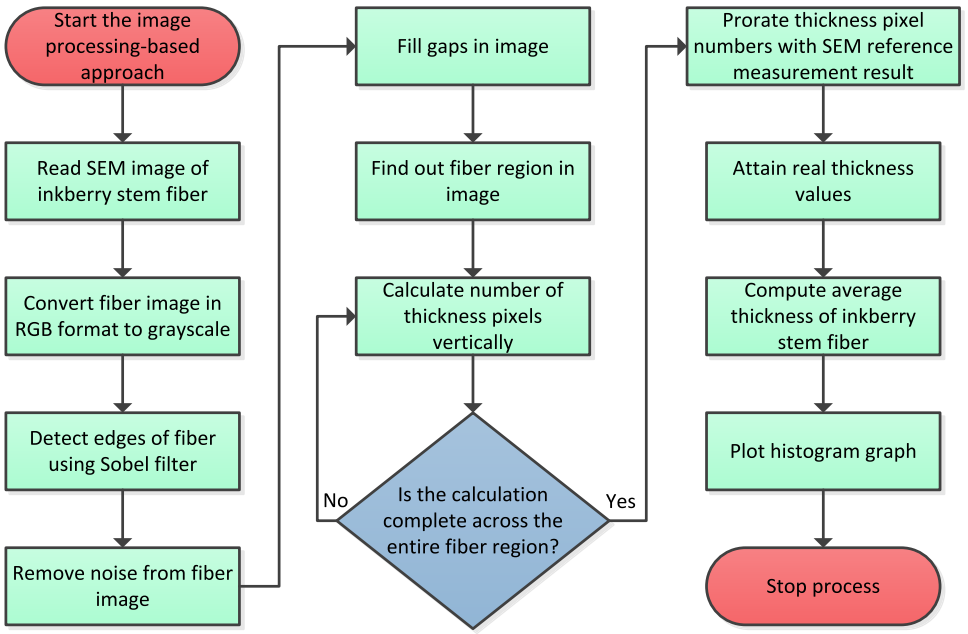

Fig. 2 Presented image processing-based approach

2.6 X-ray diffraction analysis

The X-ray analysis of inkberry fiber was achieved with a diffractometer instrument (Philips PW1820, Philips Ltd., Holland) with the intensity of Cu-Kα radiation at 0.154 nm wavelength. After X-ray diffraction analysis, the crystallinity index (Crl) of fiber samples was figured out with Eq. 2 (Segal et al. 1959) [27]:

$$Crl = \left(1 - \frac{I_{am}}{I_{200}}\right) x100 \tag{2}$$

In this equation, I_{200} represents the intensity at $2\theta = 22$, and I_{am} indicates the minimum intensity at $2\theta = 14.9$ [24].

The crystallite size (CS) was computed by utilizing the following Eq. 3:

$$CS = \frac{K\lambda}{\beta cos\theta} \tag{3}$$

In this equation, K represents the Scherrer constant (0.84), λ indicates the X-ray wavelength (0.154 nm), θ shows the Bragg angle, and β represents the peak full width at half [28].

2.7 Thermogravimetric analysis

The thermal behaviors and stability of inkberry stem fiber were characterized with a thermal analyzer (Hitachi, STA-7300 Model) (Hitachi Ltd. Corporation, Tokyo, Japan). Firstly, the fiber samples were taken placed in a case produced alumina. After, the samples were warmed up from 30 to 1000 °C with a 10 °C per min heating rate during the test. The test was performed in high-purity nitrogen atmosphere condition.

2.8 Analysis of mechanical behaviors

Tensile force and elongation at break of inkberry stem fiber were determined with a portable strength tester (Splice-Scanner 2 Portable Strength Tester) (Mesdan Company, Puegnago del Garda, Italy) to the ASTM D3822-07 standard. Before the mechanical tests, the fiber samples were stayed at 20 ± 2 °C and 65 ± 2% relative humidity for 24 h. The tests were carried out with a 20 mm gage length and 50 N load in atmospheric conditions. During testing, the cross speed was noted as 0.1 mm/min. Further, the microfibril angle of inkberry stem fiber was computed with Eq. 4:

$$\varepsilon = \ln(1 + \frac{\Delta L}{L_0}) = -\ln(Cos\alpha) \tag{4}$$

In this formula, α, L, ΔL, and ε represent microfibril angle (°deg), gage length (mm), elongation at break (mm), and global deformation, respectively [29].

3 Results and discussion

3.1 Scanning electron microscopy analysis

The surface morphology of inkberry fiber determined using a SEM device with high solution at 250 × and

1000 × magnifications is supplied in Fig. 3. The SEM micrographs of inkberry fiber indicated the smooth surfaces with channel or groove structure. On the inkberry fiber surface, serrations and minor cracks are not observed. Lignin, hemicellulose, and other contaminants that were covered of the fiber are mostly responsible for this. In the literature, it is reported that this surface structure causes poor surface wet-out and inadequate fiber-matrix bonding [30]. Furthermore, according to the SEM micrographs, it is thought that inkberry fiber has high thermal and acoustic insulation due to the channel structure. Furthermore, the channel structure surface may gain a high bonding capacity to inkberry fiber in polymer matrix composites. It is thought that this surface structure improves the contact area with resin along composite production which develops the mechanical

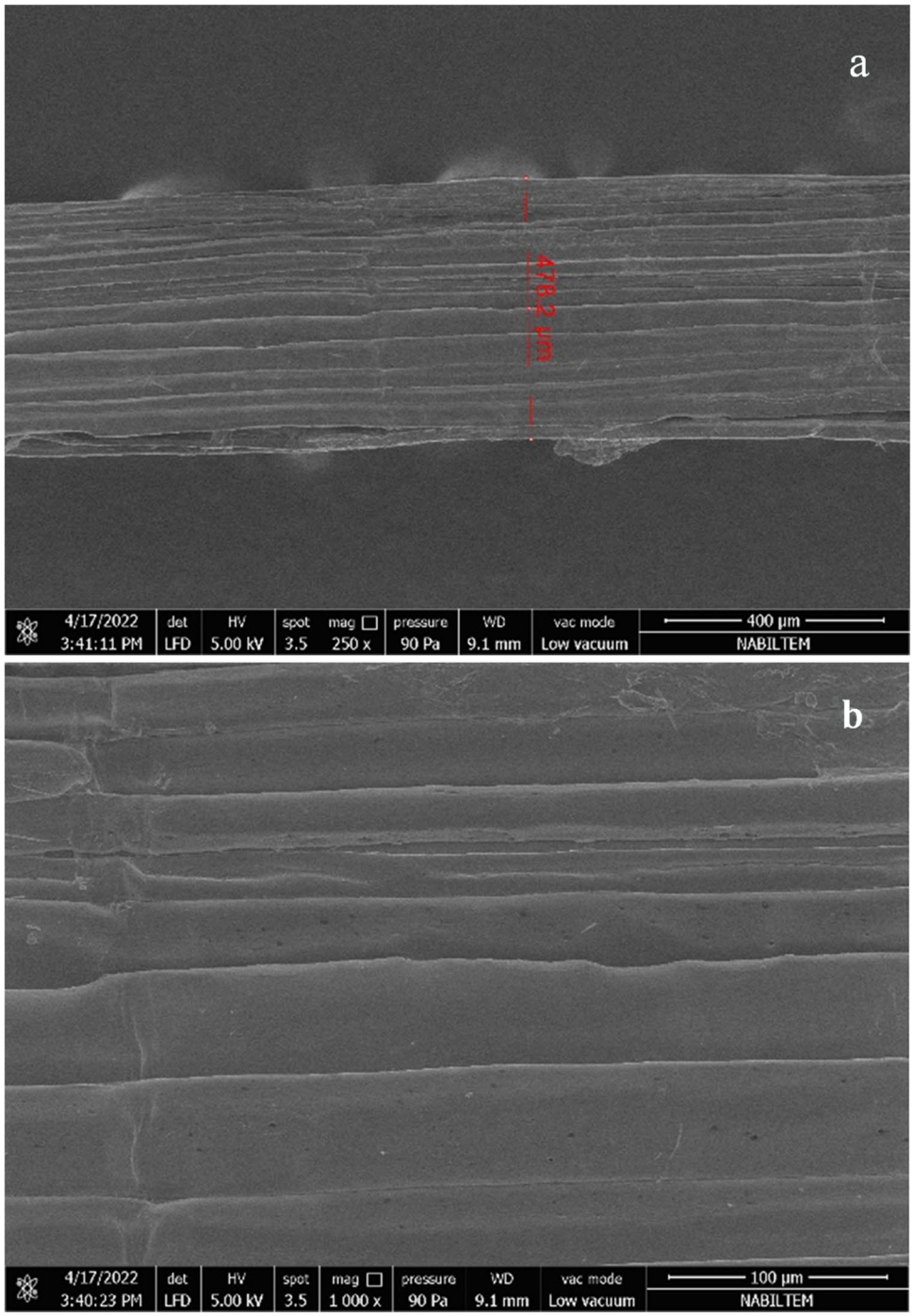

Fig. 3 SEM micrographs of inkberry fiber (**a** SEM image of inkberry fiber at 250 magnification, **b** SEM image of inkberry fiber at 1000 magnification)

behaviors of composites. In addition, it is thought that the channel structure gains to inkberry stem fiber rough surface at fiber transverse direction. The channel surface structure of the fiber may be an advantage inkberry stem fiber as remarkable reinforcement in composite materials to improve the adhesion properties of cellulosic fibers and matrix [31].

The average inkberry stem fiber thickness was predicted with image processing from SEM micrographs of fiber. The presented image processing-based approach yielded an average inkberry stem fiber thickness of 480.56. Figure 4 illustrates the histogram of inkberry stem fiber thickness.

3.2 Energy-dispersive X-ray spectroscopy analysis results

The EDX spectrum signifying the distribution of different element's existence on the surface of inkberry fiber is given in Fig. 5. The element's existence on the inkberry fiber surface in regard to weight and the atomic percentage is summed up in Table 1. The spectrum evidences the presence of high-intensity peaks of elements such as oxygen and carbon, which are previously owing to the fact that cellulose substance is mainly composed of these two elements. The oxygen and carbon peaks are determined at 0.55 keV and 0.25 keV. The existence of hemicellulose and lignin as inkberry fiber components may be validated from the high fraction of carbon (58.27 at.%) compared with oxygen (41.70 at.%), respectively. The presence of calcium with a low fraction presents the amorphous constituents of inkberry fiber, which are lignin, wax, and other impurities [13].

The compared elemental fractions of some other plant-based fibers with inkberry fiber are given in Table 2. According to Table 2, inkberry fiber has similar elements and fractions with some other plant-based cellulosic fibers.

3.3 Thermogravimetric analysis results

The thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of inkberry fiber are demonstrated in Fig. 6. The TG and DTG curves indicate that inkberry fiber thermal degradation results in three stages. The first degradation occurs at 50.56 °C with 12.13% weight loss attributed to the vaporization of water in the nature of cellulosic fiber. No weight loss was observed in the TG analysis until 330.91 °C, which may be accepted as a thermal stability factor of fiber. The remarkable degradation was specified between 50.56 and 330.91 °C, resulting in the second phase. In the second phase, the weight loss was determined as 63.07%, which attained hemicellulose degradation. The significant peak between 330.91 and 435.37 °C evaluates the decomposition of cellulose and volatile materials with 6.04% mass loss. In addition, lignin aromatic structure decomposition was determined between 200 and 800 °C [32]. According to the literature, it is reported that similar TG and DTG curves were determined for *Carica papaya* bark [33], reddish shell bean [11], *Carex panicea* stem, and *Calotropis gigantea* fruit bunch [34]. Cellulose is the main compound of natural fibers, and its structural order (crystallinity) affects the

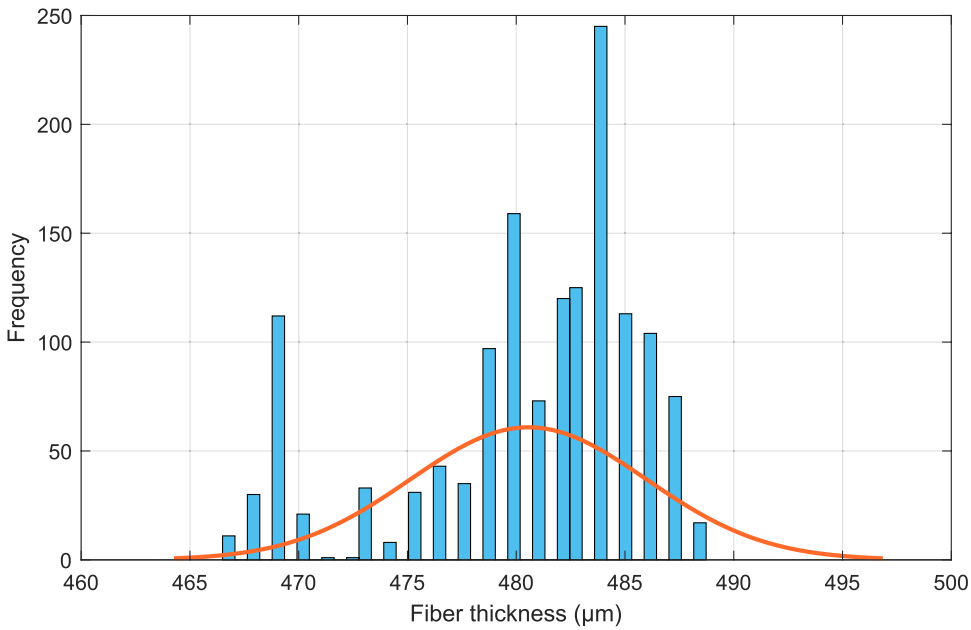

Fig. 4 The thickness histogram of inkberry stem fiber

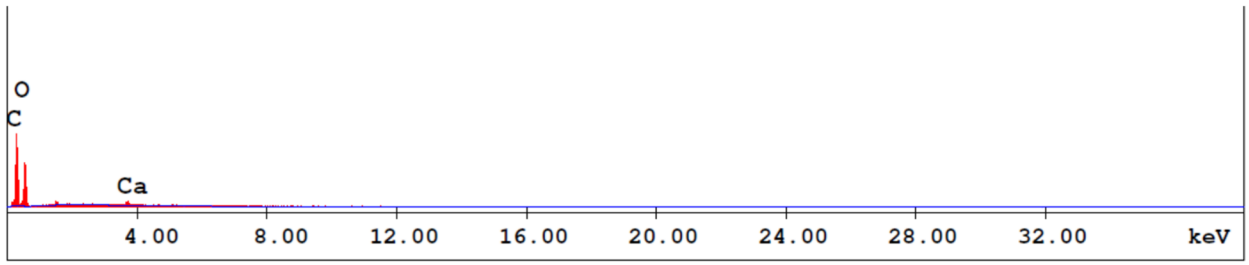

Fig. 5 EDX analysis of inkberry fiber

thermal resistance of the fibers. Cellulosic fibers with higher crystallinity are more resistant to heat because the crystalline structure conducts heat less. The microscopic structure of the fibers, i.e., the thickness and arrangement of the cell wall, affects their thermal strength. Thin fibers have higher thermal resistance than thick fibers. The thermal stability of cellulosic fiber is a main factor that determines the usage area. It is determined by the DTG and TG analysis that inkberry fiber can be used in polymer matrix composites as a reinforcement. Table 3 shows the comparative of thermal characteristics of inkberry stem fiber with some novel plant-based fibers.

3.4 XRD analysis results

X-ray diffraction (XRD) is defined as a structural analysis technique based on the X-ray diffraction of a sample. The technique provides a way to reach technical information about polycrystalline and microphase of matter. The X-ray pattern of inkberry stem fiber is given in Fig. 7. According to the diffractogram, two major peaks are seen. The first peak (at $2\theta = 14.9$ deg) is attributed to the cellulose I crystallographic plane [1 −1 0]. The second peak was determined at $2\theta = 22$ deg, responding to the amorphous fraction [2 0 0] [49]. The crystallinity index (*Crl*) of inkberry stem fiber was calculated to be 51.4%, which is higher than date palm (38.5%) [50], coconut (41.9%) [51], *Grewia tilifolia* (41.7%) [52], *Acacia leucophloea* (42%) [53], *Furcraea foetida* (42.7%) [54], *Prosopis juliflora* (46%) [55], and *Cyperus compactus Retz.* (Cyperaceae) (37.08%) [19] and lower than *Raffia Textilis* (64%) [56], sisal (71%) [56], *Sansevieria ehrenbergii* (52.27%) [57], hemp (88%) [56], flax (80%), and Bitter Albizia tree (57.20%) [45]. The plant source from which the fiber is obtained affects the crystallinity index of cellulosic fibers. Celluloses from different plants can naturally have different levels of crystallinity. In addition, the shape of cellulose fibers (e.g., the arrangement of microfibrils) and their size can also influence the crystallinity index.

The crystalline size (CS) of inkberry fiber is calculated as 4 nm. It is known from the literature that the amorphous structure of fibers decreases with the increase in the crystalline size of fibers. Stated otherwise, the fiber's high crystalline size indicates that it is extremely crystalline, indicating a raised macromolecule chain arrangement. Furthermore, the higher crystalline size reduces hydrophilic character and increases the mechanical behaviors and chemical responsiveness of fibers [5].

Table 1 EDX analysis of inkberry fiber

Inkberry stem fiber		
Elements	Weight (%)	Atomic (%)
C	51.16	58.27
O	48.76	41.70
Ca	0.08	0.03

3.5 Fourier transform infrared analysis

Fourier transform infrared (FTIR) spectroscopy is a highly effective method that measures the vibration modes of molecular bonds to give a helpful image of the functional groups and chemical bonds present in a sample. FTIR can provide a qualitative and quick observation with regard to the functional groups of inkberry stem fiber. It has been generally used for the characterization of natural and synthetic substances. FTIR spectra of inkberry stem fiber have common absorption peaks as many other cellulosic fibers at 3340.1, 2918.7, 1731.6, 1417.1, 1238.8, 1023.6, 664.8, and 552.7 cm^{-1} (Fig. 8) [58]. According to Fig. 8, a huge absorption band was determined around 3340.1 cm^{-1}, responsible for the hydroxyl group (-OH) of the intra-molecular hydrogen bond. Another peak was observed at 2918.7 cm^{-1}, which is related to C—H.

Stretching vibration of all hydrocarbon constituents and C—H stretching vibration from the -CH_2 group of

Table 2 Comparison of different elements scanned on the surface of inkberry fiber with some other cellulosic fibers [13]

	Leucaena leucocephala		Cornhusk		Jute		Cotton		*Furcraea foetida*		Inkberry	
Elements	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
C	52.81	61.65	62.64	69.17	55.68	62.72	46.1	53.2	66.43	72.50	51.16	58.27
O	40.93	35.87	36.80	30.56	43.89	37.11	53.9	46.8	33.57	27.50	48.76	41.70
Na	0	0	0	0	0	0	0	0	0	0	0	0
Mg	0.18	0.11	0.13	0.07	0	0	0	0	0	0	0	0
Al	0.10	0.05	0	0	0	0	0	0	0	0	0	0
Si	0	0	0.20	0.10	0.11	0.06	0	0	0	0	0	0
P	3.04	1.09	0	0	0	0	0	0	0	0	0	0
Cl	0.73	0.29	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0	0
Ca	0.86	0.30	0.33	0.11	0	0	0	0	0	0	0.08	0.03
S	0	0	0	0	0.08	0.18	0	0	0	0	0	0

hemicellulose and cellulose. The peak at 1731.6 cm^{-1} accounted for the carbonyl groups (C = O) of hemicellulose and lignin. The wave number at 1417.1 cm^{-1} is responsible for the (CH_2) groups of cellulose. The peak taken place at 1238.8 cm^{-1} illustrates (-COO) groups of hemicellulose. The band near 1023 cm^{-1} is connected with the O–H and C-H stretch, which is derived from hemicellulose. The little peaks around 664.8 and 552.7 cm^{-1} deal with (C–OH) group's out-of-plane bending vibrations, including ring structure; it decreases in plant maturity [5]. According to the FTIR analysis, the results have indicated the existence of major components (lignin, cellulose, and hemicellulose) in inkberry stem fiber [46]. FT-IR peak positions and relevant chemical composition in inkberry fiber are given in Table 4.

The functional groups within the fiber sample involve bonds that absorb the energy from the vibration and radiation at different frequencies, which can be classified as weak, medium, or strong depending on the bond strength. Because of the unique bonding patterns of each molecule in the fiber sample, peaks at particular frequencies are produced. The shape and size of these peaks supply information about quantities of different materials [48].

3.6 Single fiber tensile strength

The tensile behaviors of inkberry stem fiber were analyzed under a 20 mm gauge length. The average tensile strength, fiber diameter, Young's modulus, and elongation at break of the fiber are given in Table 5 tabularized with some other cellulosic fibers. Table 5 indicates that the tensile strength of inkberry fiber is higher than that of the *Kigelia africana* fruit (73.12 MPa) [59], reddish shell bean (111 MPa) [11], and *Tridax procumbens* (25.75 MPa) [60] and lower than *Dracaena draco* (555 MPa) [23], *Sansevieria cylindrical* (673 MPa) [56], *Prosopis juliflora* (558 MPa) [61], palm (377 MPa) [45], and Bitter Albizia tree (513 MPa) [45]. The elongation at break of inkberry fiber was determined as 2.37%, and the Young's modulus was estimated as 24.8 GPa. According to Table 5, it can be deduced that inkberry stem fibers have a cellulosic natural fiber, which is sufficiently strong. As seen in Table 5, the physico-chemical properties of cellulosic fibers differ from each other. The parameters affecting the mechanical properties of cellulosic fibers spread over a wide range. These vary depending on the physical, chemical, and environmental conditions of the fibers. All cellulosic fibers have different moisture content. As the moisture content of the fiber increases, the Young's modulus of fibers decreases, and the elongation capacity increases. The longer and finer the fibers tend to show more strength. High crystallinity increases the strength of the fibers, while the amorphous structure increases the

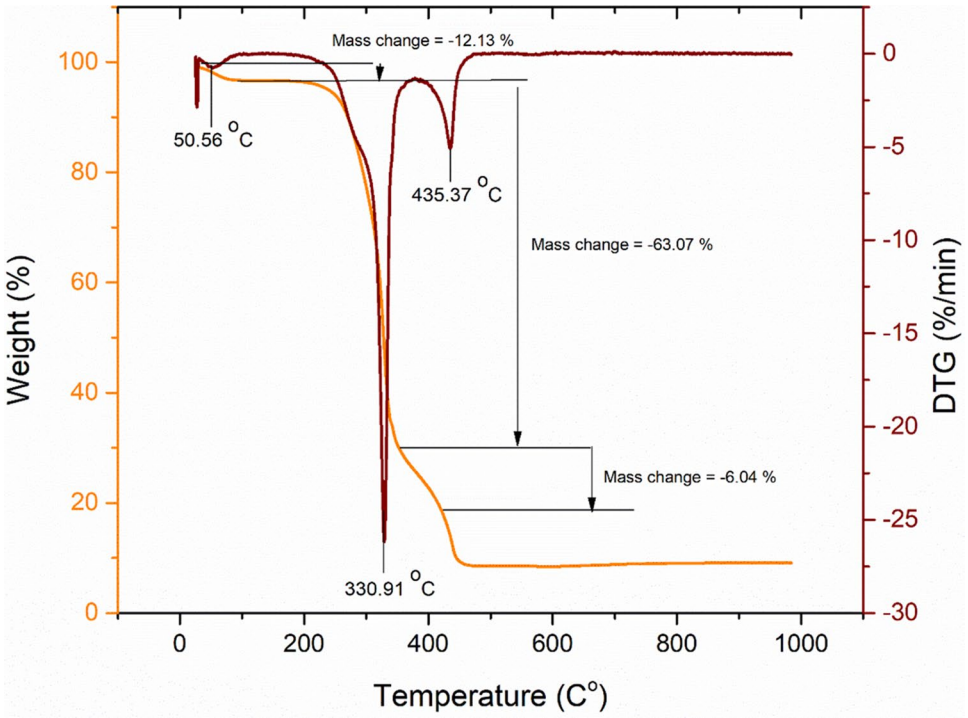

Fig. 6 The TGA/DTG graphs of inkberry fiber

flexibility and elongation capacity of the fibers. To summarize, the mechanical characteristic properties of cellulosic fibers (Young's modulus, fiber thickness, tensile strength, fiber density, and elongation at break) vary from plant source, plant age, fiber cell wall number, cultivation region, fiber extraction method, and mechanical test conditions. Furthermore, cellulose content is a significant parameter that affects the mechanical strength of plant-based natural fibers. All these parameters had an effect on the mechanical properties of inkberry fiber.

Table 3 Comparative of thermal characteristics of inkberry stem fiber with some novel cellulosic fibers

Fiber	Initial degradation temperature (°C)	Final degradation temperature (°C)	Moisture content (%)	Residual content (%)	References
Brassica oleracea var. Italic	293.05	365.05	8.39	15.02	[35]
Lavender	291.55	362.99	6.42	13.75	[36]
Alcea rose L	291.05	361.39	14.19	13.62	[37]
Beetroot	288.09	358.54	11.57	17.70	[38]
Sambucus ebulus L	346.83	456.98	6.44	25.58	[12]
Reddish shell bean	328.23	469.19	5.53	30.47	[11]
Musa paradisiaca L	189.9	368.1	9.1	18.8	[39]
Pigeon pea	250	358	11.3	19.4	[40]
Cardiospermum halicacabum	240	373	8.13	32.16	[41]
Tithonia diversifolia	204.16	376	5.57	18.91	[42]
Cyperus papyrus	245.5	383.3	-	-	[43]
Bauhinia vahlii	233.44	368	9.83	15.65	[44]
Abutilon indicum	175	302	-	-	[16]
Bitter Albizia tree	138	334	-	23.35	[45]
Habara plant stem	130	204	28.25	5	[46]
Water lily	231.1	338.5	12.31	20.1	[47]
Grewia ferruginea	150	275	18.25	5.7	[48]
Inkberry	330.91	435.37	12.13	18.76	Recent study

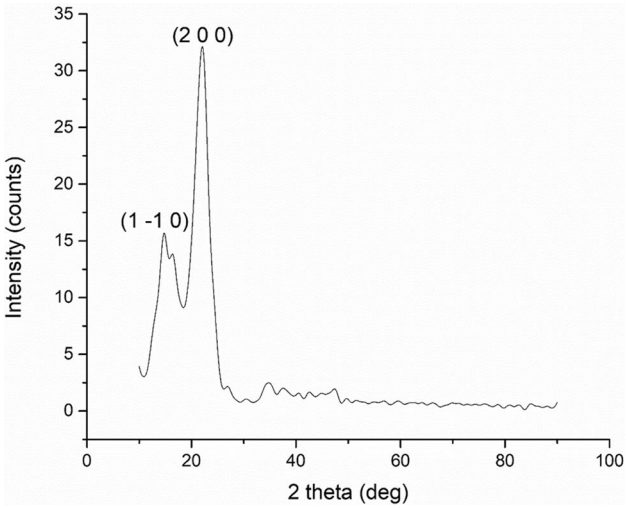

Fig. 7 The XRD graphs of inkberry fiber

Table 5 shows that inkberry fiber has 480.56 µm fiber thickness and 1400 kg/m^3 fiber density. It is deemed that the low thickness of the fiber is owing to the structure of the inkberry plant fiber. Because the fiber contains a large amount of cellulose, its high density can be explained [71]. Inkberry fiber density is determined as higher than some original cellulosic fibers, such as *Abutilon indicum* (1170 kg/m^3) [71], *Streblus asper* (1388 kg/m^3) [72], *Spinifex littoreus* (780 kg/m^3) [73], and *Himalayacalamus falconeri culms* (1300 kg/m^3) [74] and lower than *Hibiscus canescens* (1425 kg/m^3) [75].

Microfibril angle is a significant factor affecting tensile rate. A large microfibril angle causes high ductility, and a small angle induces higher strength. The microfibril angle of inkberry fiber for a 20 mm gage length was assigned as 33°. In the production of fiber-reinforced composites, the use of smaller microfibril angle fibers is commonly chosen [59].

4 Conclusion

In this study, the properties of a novel cellulosic fiber extracted from the inkberry plant stem were investigated to evaluate the possibility of using it as reinforcement in composite materials. The study of the surface morphology by SEM revealed that inkberry fibers have a channel structure. Elemental analysis results demonstrated that inkberry fiber occurs from carbon and oxygen elements responsible for cellulose structure. Inkberry fiber has a high crystallinity index (51.4%) that supports the high tensile strength (146.5 MPa) and high Young's modulus (24.8 GPa). Furthermore, inkberry fiber was obtained to propose high ductility, which is approved from the high

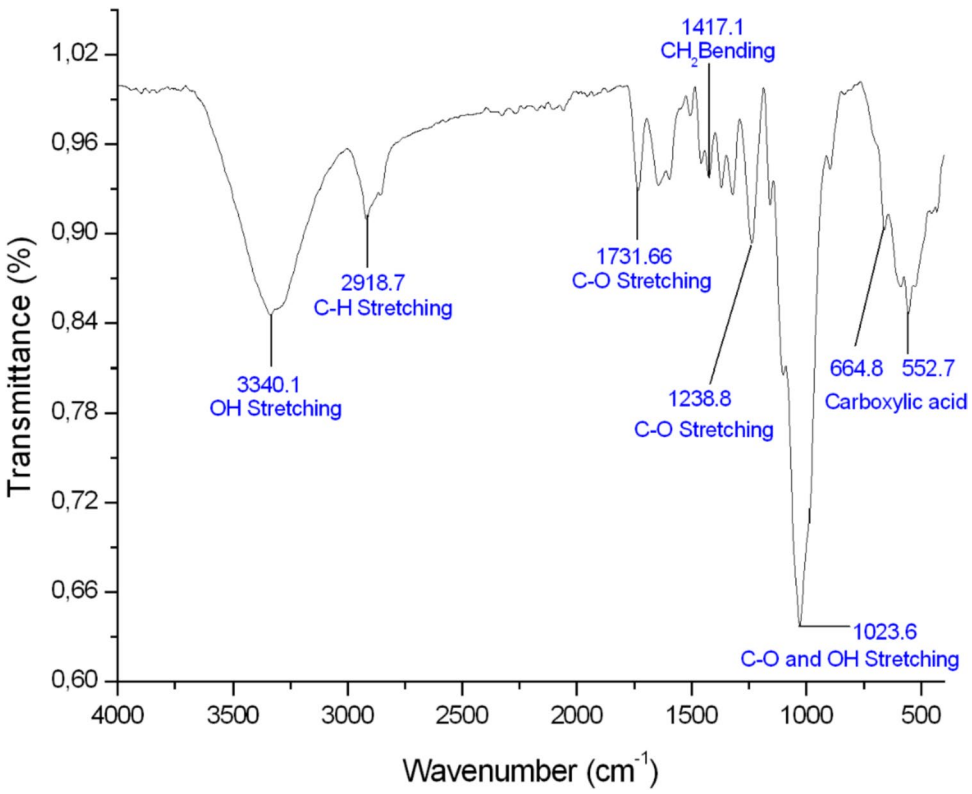

Fig. 8 The FTIR spectrum of inkberry fiber

Table 4 FT-IR peak positions and relevant chemical composition in inkberry fibers

Peak positions (cm^{-1})	Functional group	Relevant chemical composition	Reference
3340.1	-OH	Cellulose and hemicellulose	[5]
2918.7	CH_2	Cellulose and hemicellulose	[5]
1731.6	C=O	Hemicellulose and lignin	[5]
1417.1	CH_2	Cellulose	[5]
1238.8	-COO	Hemicellulose	[5]
1023.6	C-H, O–H	Hemicellulose	[5]

microfibrillar angle of 4 nm. Thermogravimetric analysis results show that inkberry fibers represent a maximum thermal stability of 435.37 °C. Elemental components were carried out with EDX analysis, and maximum peaks were determined from carbon, oxygen, and calcium with 51.16 wt.%, 48.76 wt.%, and 0.08 wt.%. The existence of carbon and oxygen in higher quantities indicates that inkberry stem fiber is cellulose-based in nature. Morphological micrographs show that inkberry fiber has smooth surfaces with channel or groove structures. FTIR analysis proves the existence of components such as cellulose (-OH and CH_2 stretch), hemicellulose (-OH, CH_2, C=O, -COO, C-H, and O–H), and lignin (C=O). High thermal stability, lower thickness, and high mechanical behaviors confirm that inkberry fiber may be recognized as a promising reinforcement fiber in polymer matrix composites for many non-structural applications which are interior body panels in yachts, automobiles, partition boards in buildings, and barriers. The characteristic results revealed that inkberry stem fiber has comparable behaviors to other cellulosic natural fibers. Furthermore, inkberry fiber gained from

Table 5 Characteristic values for density, diameter, crystallinity index, and mechanical behaviors of some cellulosic-based natural fibers

Fiber	Density (kg/m^3)	Thickness (μm)	Crystallinity index	Tensile strength (MPa)	Young's modules (GPa)	Elongation at break (%)	References
Carica papaya bark	943	-	56.34	530	-	1.62	[33]
Bauhinia vahlii	-	-	56	62.28	3.22	2.25	[44]
Arial roots of banyan tree	1234	0.14	76.35	19.37	0.7	1.8	[18]
Cryptostegia grandiflora	1020	117	62	791	-	3.1	[62]
Fishtail palm	1473	380.85	31.37	249.23	-	2.01	[63]
Dracaena draco	1204.3	-	30.42	553	24.9	2.5	[23]
Tabernaemontana divaricate	1460	321	62.9	249.25	-	2.72	[14]
Chamaerops humilis rachis	801	241.23	68.38	110.85	6.05	2.29	[64]
Sansevieria cylindrica	915	100	60	673	6.72	10.04	[56]
Cyperus compactus Retz	-	399.1	37.08	943	97.43	1.07	[19]
Leucaena leucocephala	1470	-	63.10	415	9.90	4.33	[13]
Abutilon indicum	1170	175	77.35	-	-	-	[16]
Purple bauhinia	1460	511	54.98	373.3	5.31	6.9	[65]
Kigelia africana fruit	1316	507	57.38	73.12	8.76	0.92	[59]
Hierochloe odarata	1160	136.71	63.8	105.7	2.56	2.4	[66]
Derris scandens	1430	158	58.15	633.87	13.54	6.56	[5]
Reddish shell bean	1580	785	-	111	6.11	1.83	[7]
Lavender	870	295	-	226	7.6–4.8	2.9–4.6	[36]
Dracaena reflexa fiber	790	176	-	829	46.3	2.9	[67]
Cymbopogon nardus	-	-	49.7	435.9	55.2	1.3	[68]
Pongamiapinnata L	1345	-	45.3	322	9.6	2	[49]
Prosopis juliflora	580	-	46	558	-	1.7	[61]
Lygeum spartum L	1499	-	46.19	280	13.2	3.7	[49]
Symphirema involucratum	1389	-	28.22	397.2	4.5	6.7	[69]
Elephant grass	-	70–400	-	292.3	10.4	2.8	[70]
Aleo vera	1330	80	52.6	805.5	2.39	42.29	[28]
Tridax procumbens	1160	233.1	-	25.75	0.94	2.77	[60]
Inkberry	1400	480.56	51.4	146.5	24.8	2.37	Recent study

renewable source has led to the discovery of cellulosic natural fibers. It is recommended to utilize inkberry stem fiber as a substitute fiber to synthetic fibers used in composites for decreasing environmental pollution.

Author contribution S.E. carried out physico-chemical analysis of inkberry stem fiber and interpreted the results. C.E. developed and implemented an image processing method to determine the average fiber thickness of inkberry fibers. N.M. collected inkberry plant and extracted the inkberry fiber from plant stem. All authors wrote and reviewed the main manuscript.

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

Declarations

Ethics approval The authors confirm that there was no ethical issue in preparing this manuscript.

Consent to participate All authors consent to participate in this work.

Competing interests The authors declare no competing interests.

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