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REVIEW

Recycling of bast textile wastes into high value-added products: a review

Xue Yang[1,6] · Wei Fan[1,6] · Hui Wang[2] · Yang Shi[3] · Shujuan Wang[4] · Rock Keey Liew[5] · Shengbo Ge[3]

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Abstract

The textile industry contributes to about 5% of all waste globally, with approximately 20 billion pounds of waste landfilled every year, calling for advanced recycling methods in the context of the circular economy. Here, we review physical and chemical methods for recycling textiles waste into high value-added products such as composite reinforcements, soil covering materials, adsorbents, electrodes, supercapacitors, and nanocrystalline cellulose. Chemical recycling is more frequent than physical recycling. Product quality depends on the recycling methods; for instance chemical recycling yield materials with better porous characteristics and higher adsorption capacity than materials obtained by physical recycling. Intelligent wearables and technologies for advanced textile processing are discussed.

Keywords Bast fibers · Textiles waste · Recycling · Circular economy · Chemical recycling · Physical recycling · Composite · Adsorbent · Cellulose

Introduction

Bast fibers are derived from various basts that have recently gained popularity due to their low cost, low density, biodegradation, and excellent mechanical properties (Bourmaud et al., 2018; Kalia et al., 2009; Yan et al., 2016). They are not only used in traditional textile fields but also widely applied to industrial textile fields, such as camping tents, fishing nets, ropes, and car cushions (Ip and Miller, 2012; Ramamoorthy et al., 2015; Ramesh et al., 2017). Bast fibers include hemp, ramie, flax, sisal, kenaf and jute (Choi and Lee, 2012; Crini et al., 2020; Yu et al., 2014), of which hemp is called *Cannabis sativa L.* (Candy et al., 2017; Kuglarz and Grübel, 2018), consisting of 70% cellulose (Schettini et al., 2013). Ramie is a unique product that originated in China (Feng et al., 2011; Yang et al., 2021) with moisture absorption and permeability are about 3-5 times that of cotton fibers, along with bacteriostatic behavior, mildew resistance, ventilation and cooling (Cai et al., 2020; Dang et al., 2019). In addition to being the oldest textile fiber in the world, flax is native to the Mediterranean and Southwest Asia. Its round or oblate shape makes it superior in heat dissipation and moisture absorption when wet. Jute usually grows in warm, humid climates, while the shape is polygonal, with varying canal sizes, and provides excellent strength, toughness, elastic modulus, and moisture absorption (Ivanovska et al., 2019). Sisal is a perennial tropical hard leaf fiber (Sever, 2016), originated in Mexico (Luhar et al., 2019) and is mainly grown in Africa, North America and Asia (Ye et al., 2015). It is the hardest fiber with a crescent or horseshoe shape,

✉ Wei Fan
fanwei@xpu.edu.cn

✉ Shengbo Ge
geshengbo@njfu.edu.cn

[1] School of Textile Science and Engineering, Xi'an Polytechnic University, Xi'an, Shaanxi 710048, China

[2] College of Environmental Science and Engineering, Donghua University, Shanghai 201620, China

[3] Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, International Innovation Center for Forest Chemicals and Materials, College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, Jiangsu 210037, China

[4] School of Chemistry, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

[5] Pyrolysis Technology Research Group, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia

[6] Key Laboratory of Functional Textile Material and Product (Xi'an Polytechnic University), Ministry of Education, Xi'an, Shaanxi 710048, China

the largest amount and the widest planting range today. Kenaf is a relatively new annual fiber resource introduced from abroad in the early twentieth century in China, which is an essential raw material for the bast spinning and paper industry due to its strong resistance to environmental stress. With the economic growth in recent years, the demand for biodegradable, green and environmentally friendly bast products has increased. Meanwhile, the waste associated with bast resources is becoming increasingly severe. Therefore, appropriate measurements are required to deal with the increasing generated bast textiles waste effectively.

Generally, many textiles waste is disposed of by burning in municipal waste incinerators or landfills (Wang et al., 2022). Incineration will produce lots of toxic gases and carbon dioxide, polluting the atmospheric environment and producing the greenhouse effect (Lu et al., 2022; Wu et al., 2017; Yu et al., 2021), while landfills will release undesirable chemicals into the soil, causing soil and water pollution (Meng et al., 2019; Rago et al., 2018). Evidence has shown that both incineration and landfilling are considered less efficient ways to treat bast textiles waste (Xu et al., 2019). In facing the new requirements (carbon neutrality, emission peak) of environmental protection (Cao and Wu, 2008), appropriate recycling of bast textiles waste through effective and scientific methods to produce new raw materials with similar properties or new functions is necessary to realize a circular economy.

In the precondition to guaranteeing environmental security, recycling aims to ensure the good use of resources and protect the environment by using advanced technologies to transform the waste generated during the production and consumption processes into reusable resources and products (Nzioka et al., 2018). Currently, various methods are used to recycle bast textiles waste, including physical recycling (Brzyski et al., 2017; De Silva and Byrne, 2017; Renouard et al., 2017), chemical recycling (Marinho et al., 2020; Williams and Reed, 2004) and energy recycling (Ghoushji et al., 2017; Yi et al., 2013; Sandin and Peters, 2018). Physical recycling employs mechanical equipment to reprocess bast textiles waste into fibers. The obtained product is available as a material for filling, sound insulation, heat insulation of wall insulation layer and bathroom wall tiles (Gebremedhin and Rotich, 2020; Muthuraj et al., 2019). Chemical recycling represents turning waste materials into valuable ingredients using a substantial amount of chemical means (Ouchi et al., 2010).

In contrast, thermal energy generation during incineration of bast textiles waste is considered energy recycling. Moreover, several products are generally obtained after the recovery and utilization, such as reprocessed fiber fabrics, non-woven fabrics, processed fibers filling, and reclaimed cellulose fibers. The recycling of the bast textiles waste, thus, improves the textile enterprises concerning the circular economy model, thereby enhancing the value of the materials and promoting social progress (Navone et al., 2020).

This review aims to highlight the recycling methods of bast textiles waste. Firstly, the application of bast textiles waste in reinforcements, soil covering materials, papermaking materials, cellulose, nanocellulose and nanocrystalline, adsorbents, electrode materials and supercapacitors is summarized and discussed via physical and chemical recycling methods. Secondly, the future recycling methods of the bast textiles waste were prospected. Finally, we hope that the bast textiles waste can be recycled effectively and prepared into functional filaments, papers, battery diaphragms, three-dimensional (3D) reinforcements of composites, electrode materials and other products in the future, reforming a short-process, high-value, pollution-free and zero-emission recycling method.

Physical recycling

Physical and chemical methods are the principal methods for recycling bast textiles waste in which products recovered by these ways can be remanufactured into industrial textiles, cellulose, nanocellulose, cellulose nanocrystalline, adsorbents, electrodes as well as supercapacitors, thus further enhancing the value of the textile wastes and forming the circular economy model of “natural resources-products-renewable resources” (Nagarajan et al., 2020). The current efforts of these two methods will be detailed in the following sections.

Bast textiles waste recovered by physical methods can be reprocessed into industrial textiles and absorbents. Industrial textile refers to textiles used in various industries, such as agriculture, animal husbandry, construction, transportation, and other cutting-edge scientific fields. These textiles can also be described scientifically as technical or high-performance textiles. Currently, the bast textiles waste application in industrial textiles mainly includes the reinforcements of composites and soil covering materials (Laborel-Préneron et al., 2017).

Composite reinforcements

Bast fibers and fabrics attract research attention due to their fast growth, low density, high specific strength, rigidity and sound absorption (Kalusuraman et al., 2020; Kuciel et al., 2019), and their composites have been extensively employed in automobiles, civil, furniture, and construction industries (Ge et al., 2020; Lu et al., 2020; Zhang et al., 2021). The reinforcement structures are mainly divided into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D) and 3D structures from structural dimensions and

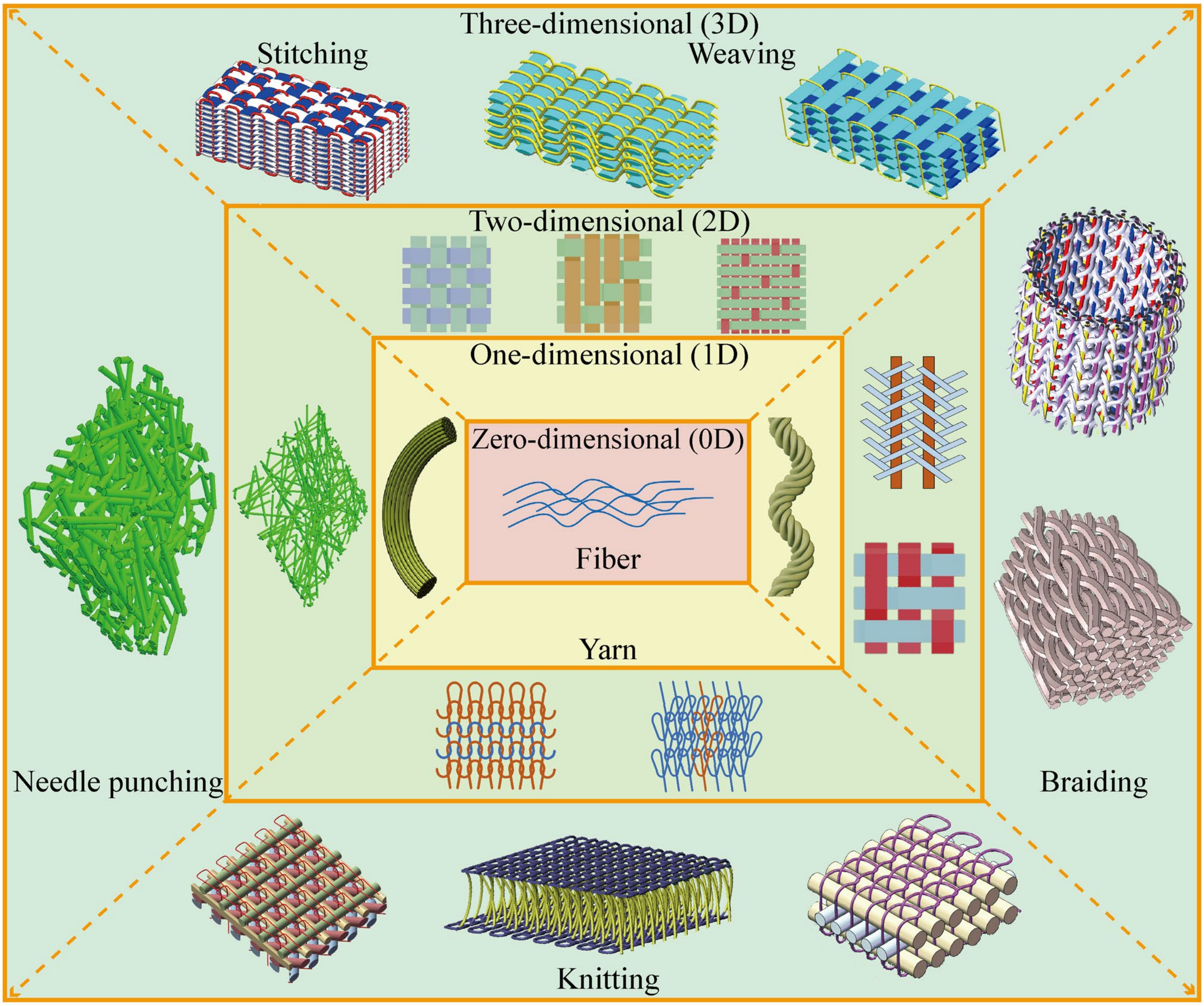

Fig. 1 Classification of reinforcement structures. According to the structural dimensions and manufacturing processes of materials, the reinforcements are generally divided into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. As a 1D structure, the yarn is made of fibers through the spinning process. The 2D structure includes weaving, braiding, knitting, stitching and non-woven structures according to the different manufacturing processes. By introducing yarns in the direction of thickness, various 2D structures can be turned into 3D structures

manufacturing processes, as shown in Fig. 1. The 0D and 1D structures include fibers and yarns. These are regarded as the smallest structural unit for preparing reinforced materials. Among these, yarn is indicated by the arrangement of the textile fibers in a particular orientation to form an elongated fiber assembly with specific mechanical properties by twisting or entangling the fibers. Weaving, knitting, braiding, stitching, and non-woven processes can develop fibers and yarns into 2D and 3D structures with specific dimensions. The weaving structures can be further divided into plain, twill and satin, in which plain is formed by interweaving the warp and weft yarns one by one, while twill results from the interweaving of the two at a certain angle and satin represent a single tissue point on each warp and weft yarn.

Knitting is a process of preparing fabric using knitting needles to hook various yarns into a coil and subsequently connect them into a series of sets, which covers warp knitting and weft knitting with specific elasticity and flexibility suitable for use for towels, sweaters and other products. Braiding structure is the same as the production process of mats and braids, composed of two or more sets of misaligned and interwoven strips (Dong et al., 2020). It can be made into products of flat, tubular or other shapes due to its simple manufacturing process. Stitching is sewing the laminated fabric with yarn (Abdelal and Donaldson, 2018). Non-woven technology refers to the sheets and webs developed by directional or randomly arranged fibers by friction, amplexation, or bonding methods. Among these, needle punching technology is a typical non-woven process which uses the puncture effect of the needle to strengthen the fluffy web into a fabric. A 3D structure can be generated by introducing the yarn in the thickness direction of the 2D structure, which can enhance the overall mechanical performance of the material. 3D orthogonal and 3D angle interlock structures are the two commonly used structures in 3D weaving technologies, which have integral properties (Fan et al., 2022) and improve the performance of the woven in the thickness direction.

Moreover, two flat fabric pieces are vertically connected by fibers or yarns to form a 3D knitted structure, known as the knitted spacer fabric. It has excellent hygroscopicity, moisture conductivity and filterability, thus finding use in agriculture, medical treatment, entertainment, among other uses. 3D braiding is based on the 2D braiding process to enhance the axial fiber to braid 3D fabric. After continuous development, 3D four-directional, 3D five-directional, 3D six-directional, and 3D seven-directional structures can be manufactured (Zheng et al., 2017). 3D stitching structure achieves by introducing yarn in the thickness direction of the laminated fabric. This structure has excellent interlayer properties and impacts damage tolerance (Song et al., 2022). The needle in the *Z* direction can pierce the fiber into the felt, thus allowing the preparation of felt with a 3D structure. This structure can meet the requirements for excellent mechanical performance materials.

Nowadays, there are many strategies to develop reinforcements from the bast textiles waste. For example, Holser (2009) directly incorporated the waste flax fibers into the mixture of glycerin and $C_6H_{10}O_4$ for preparing thermosetting composites and bio-composites. However, these materials developed directly from untreated bast fibers may not meet the application requirements in the field of mechanics. As a result, a few research studies have used bisphenol-A/bisphenol-A-based benzoxazine and silane coupling agent (or amino silane) to modify the waste hemp and jute fibers (Das et al., 2010; Panaitescu et al., 2010; Zegaoui et al., 2019). The modified methods can effectively develop the low-value fibers waste into a new type of bio-composites, thus improving their performance in residential and construction fields (Ganguly, 2009). Simultaneously, pretreated waste jute and glass yarns in terms of mercerized and resized have also been used to weave the reinforcements for composites (Masood et al., 2018). However, the mechanical properties of the material developed using the single waste jute yarns are noted to be lower than that of the composite developed using hybrid yarns. This suggests that weaving technology helps boost the performance of composites.

Moreover the (C_3H_6)n-flax non-wovens wastes were ground and re-assembled into new non-wovens, and a new composite was obtained by injection molding method (Renouard et al., 2017). The waste can also be converted into composites with thermoplastic materials such as polylactic acid or polyethylene (Battegazzore et al., 2018; Nestore and Vancovicha, 2013), exhibiting optimal bending tensile properties. Furthermore, blended yarns generated from flax fibers waste and renewable polylactic acid fibers can also be made into unidirectional composites for lightweight construction fields, demonstrating a potential upcycling process of waste (Mohl et al., 2022). Simultaneously, waste hemp reinforced composites with 30% fiber volume content show excellent mechanical, thermal, physical, and chemical properties for roofing, tents, and flooring (Jadhav and Jadhav, 2022).

Starch is a commonly used plasticizer for preparing plant fiber-reinforced cement boards. The physical and mechanical properties of the jute cement starch composite board meet the European standards and can be used for building partition walls, internal partitions and insulation (Ferrandez-Garcia et al., 2020). Moreover, waste flax can be developed into thermal insulation particleboard through hand lay-up and hot-pressing processes to replace the traditional thermal insulation materials for attaining environmental protection (Sam-Brew and Smith, 2017; Zach et al., 2016), and their mechanical properties are also enhanced to a certain extent. Meanwhile, the porous structure of the hemp fibers has specific sound absorption properties. Therefore, applying waste materials for noise control can result in cost-effective and environmentally friendly strategies (Bhingare et al., 2019; Raj et al., 2020). Tiuc et al. (2018) incorporated 10% waste flax fibers into the rigid polyurethane foam matrix to fabricate composites with high sound absorption performance. The resulted fibers were used in road, railway or air transportation fields. In the future, bast fiber composites are expected to lead to latent inhibition in basic facilities and the vehicle industry (Ge et al., 2021; Kakati et al., 2019; Radzuan et al., 2020; Chauhan et al., 2019), especially in automotive interior parts for significantly reducing the weight and cost of automobiles.

The composite preparation methods, strengths and shortcomings are summarized in Table 1. Bast textiles waste is usually ground into powder and subsequently hot-pressed with a binder to form composites with vast potential for furniture and rail transportation usage. In addition, the bast fibers can also be used for sound absorption and thermal insulation for building reinforcement. Simultaneously, various strategies have incorporated the woven bast yarns into the fabric and mixed them with the high-performance fibers to prepare the composites. These methods are effective in developing the waste fibers into functional materials. In short, these methods would provide an impetus for future research and application of the bast textiles waste in composites production.

Table 1 Preparation and reinforced structures for composites based on bast textiles waste

Materials	Preparation methods	Structure	Refs.
Hemp	Melt extrusion and hot-pressing processes	Chopped fibers	(Battegazzore et al., 2018)
Flax	Hand lay-up molding	Chopped fibers	(Hussein et al., 2019)
Jute, flax	Hot-pressing process	Chopped fibers	(Tiuc et al., 2018)
Hemp	Hot-pressing process	Chopped fibers	(Zegaoui et al., 2019)
Jute	Hot-pressing process	Chopped fibers	(Ferrandez-Garcia et al., 2020)
Jute	Hot-pressing process	Chopped fibers, non-woven fabrics	(Das et al., 2010; Ganguly, 2009)
Jute	Hot-pressing process	Chopped fibers	(Saikia et al., 2017)
Jute	Vacuum bag molding	Woven fabrics	(Masood et al., 2018)

Soil covering materials

Usually, the soil covering material is a polyethylene film with a thickness of 0.04 mm (Oz et al., 2016). The preparation process is reinforced with various functional additives to achieve thermal insulation, cooling, disease prevention, weeding, breathability, and easy operation. The bast textiles can be used as a soil covering materials due to their water-retaining properties. Therefore, efforts have been made to develop the bast textiles waste into non-woven fabrics to design uniform, porous, bulky, and mechanically wounded fiber sheets for strawberry cultivation. Among the various bast textile waste, the performance of the waste jute non-woven fabric is superior as compared to the others, suggesting that jute non-woven fabric represents a promising alternative to soil covering material (Sengupta and Debnath, 2018).

Adsorbent materials

The bast textiles are commonly used directly as an adsorbent in a large area without additional treatment due to their unique porous structure, which significantly reduces the production cycle of adsorption materials. For example, Tofan et al. (2015) used waste hemp fibers washed with soap and soda ash to adsorb Zn(II) ions in an acid medium solution. The adsorption potential of hemp fibers is unchanged after three cycles of adsorption-desorption of Zn(II). As reported in other studies, the Co(II) can also be adsorbed by waste hemp fibers (Tofan et al., 2013). These results indicate that untreated waste hemp fibers may have a good adsorption efficiency.

Chemical recycling

Chemical recycling represents another way of turning the bast textiles waste into functional components by chemical means. The chemical recycling approach is usually used in papermaking, the extraction of cellulose, nanocellulose and cellulose nanocrystalline, and the preparation of adsorbents, electrodes, and supercapacitors.

Papermaking materials

Pulpzyme has been used to treat jute from the waste woven carpets (Mohajershojaei and Dadashian, 2014) due to the pulpzyme can hydrolyze the cellulose chains and shorten the cellulose fibers. The materials produced by this method are suitable as raw materials for the papermaking process, with a width size between 0 and 4 mm.

Cellulose, nanocellulose and cellulose nanocrystalline

Cellulose is the main ingredient of the plant cell walls (Lee et al., 2010), consisting of linear chains of D-glucose units linked by β-1,4-glycosides (Deeksha et al., 2021; Ge et al., 2022; Hassan et al., 2020; Pattnaik et al., 2021). Cellulose is non-toxic, renewable, and degradable (Hamidon et al., 2022) and can be applied for papermaking, plastics, explosives, electrical engineering and scientific research equipment. Nowadays, extracting cellulose from the bast textiles waste mainly includes double asymmetric centrifugation, alkaline hydrolysis, alkali and acidification, organic acid extraction, and high-energy planetary ball milling.

Double asymmetric centrifugation extraction

The double asymmetric centrifugation method is a mechanical process that provides extra shear stress to convert the defibrillated cellulose into micro- and nano-fibrillated cellulose. Unlike the traditional centrifugation method, the

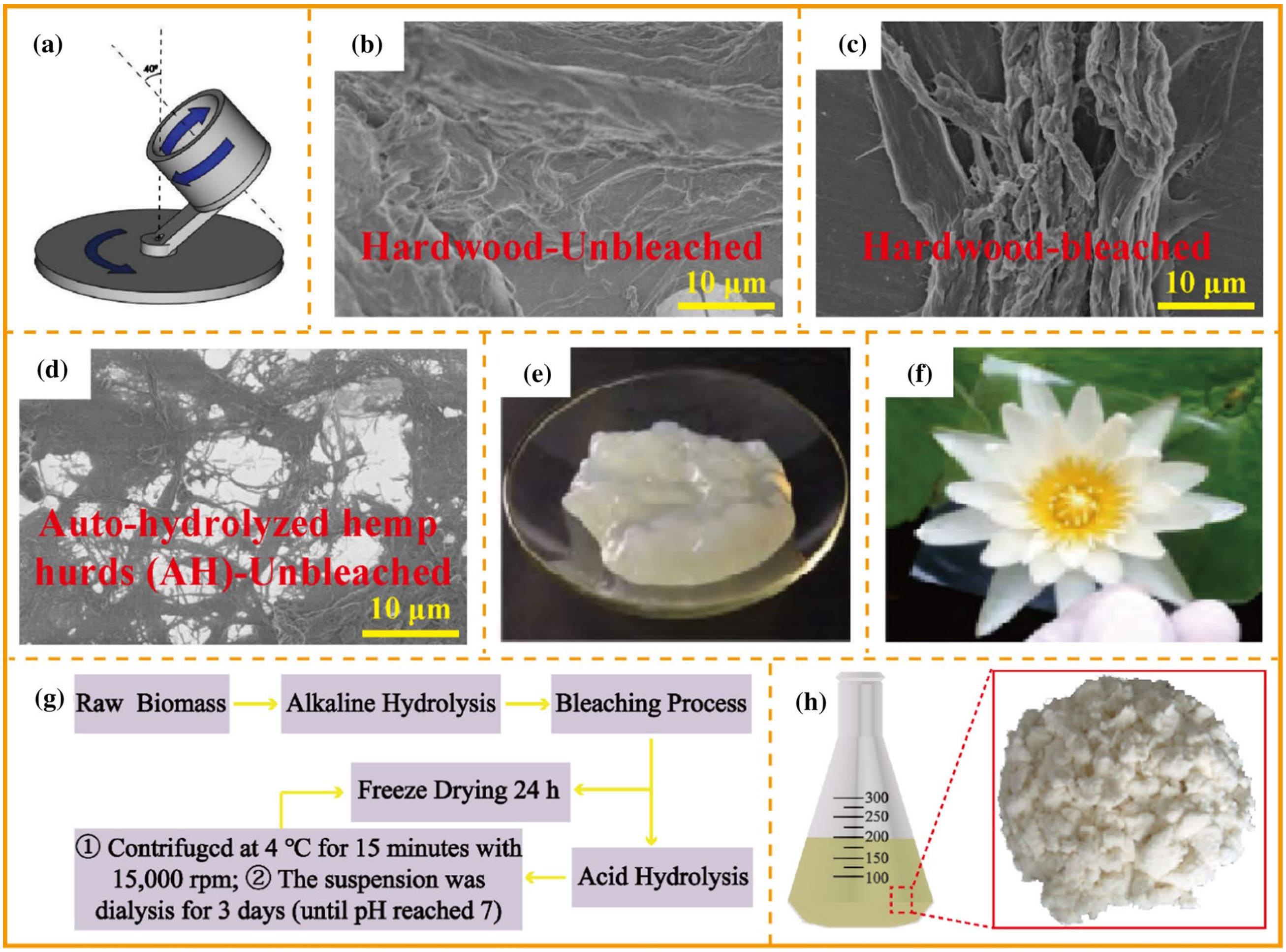

Fig. 2 Cellulose is extracted from bast textiles waste. **a-d** The equipment structure of double asymmetric centrifugation and scanning electron microscope images of different pulps treated with double asymmetric centrifugation, respectively. Reprinted with permission of American Chemical Society from Agate et al. (2020). **e** and **f** The water suspension and its casting film were prepared by high-pressure micro-fluidization with cellulose defibrillation concentration of 0.7% w/V for 120 min. Reprinted with permission of Elsevier from Pacaphol and Aht-Ong (2017). **g** The process of extracting cellulose and nanocrystalline cellulose from lignocellulosic biomass by acid and alkali hydrolysis. Reprinted with permission of Elsevier from Tuerxun et al. (2019). **h** Cellulose was separated from the waste fibers by organic acid extraction

sample not only has a certain degree of freedom of translation on the central axis, but the holder also rotates around the second axis during the process, as shown in Fig. 2a. The specific steps include pretreatment of the hemp fibers with distilled water, active alkali, and sulfate, followed by processing in a double asymmetric centrifugation container for 3 h (Agate et al., 2020). It is observed from the scanning electron micrographs (Fig. 2b-d) that the cellulose prepared from different fiber slurries is challenging, where synthesis of cellulose from the delignified fiber using this method does not coincide with the previous findings. Therefore, it is believed that although this method is simple and convenient, along with significantly reduced crystallinity of nanocellulose after treatment, however, the widely used acid and alkali methods are preferred for producing cellulose in various conditions.

Alkaline hydrolysis

Alkali hydrolysis is a commonly used method for extracting cellulose, which involves pre-treatment of the bast fibers with alkaline H_2O_2 solution, followed by heating in an alkaline reactor at a specific concentration and temperature. The higher the temperature, the more complete the heating process. Studies have reported using the alkaline hydrolysis method to extract cellulose from waste jute (Ahuja et al., 2018), hemp (Baksi et al., 2018; Pacaphol and Aht-Ong, 2017) and other bast textile wastes. The appearance of the water suspension and nano-cellulose cast film prepared from hemp is displayed in Fig. 2e, f. The defibrillation concentration of cellulose is 0.7% w/V, and the suspension and cast film prepared by the high-pressure micro-fluidization process performed for 120 min is observed to exhibit the highest transparency, thus confirming the optimal process conditions for preparing cellulose films.

Meanwhile, the thermal stability of the cellulose is also observed to be higher than that of the original fiber. The developed cellulose can also be implanted on the commercial filter paper as a barrier for the oil–water separation membranes, which has a strong commercial prospect. Although this method can eliminate many components in the waste bast fibers, the yield obtained is too low.

Acid and alkaline hydrolysis

The primary process involved in the acid-base combination method is to hydrolyze the waste kenaf fibers with a certain proportion of NaOH solution at room temperature. Subsequently, these are bleached with H_2O_2 (35%) at 75 °C for 4 h and filtered to obtain cellulose. Cellulose is further dispersed in 60 mL H_2SO_4 for hydrolysis under stirring to prepare the nano-cellulose suspension. After dialysis for 3 days, nanocellulose is obtained (Fig. 2g). At the same time, waste hemp fibers can also be recycled by this method (Abraham et al., 2016). The cellulose, nanocellulose, and cellulose nanocrystalline prepared by this method did not exhibit cytotoxicity, especially cellulose nanocrystalline possesses high modulus, large surface area, biodegradability and environmental benefits (Oyeoka et al., 2021), thus signifying the potential of their applications in the biological scaffolds and bioengineering (Tuerxun et al., 2019). Nevertheless, this process is comparatively complicated and produces a significant amount of wastewater.

Other methods

In addition to the aforementioned methods, the organic acids method has also been used to extract nano-cellulose from the waste jute fibers. Figure 2h shows a flowchart of the pulping and cellulose extraction using the organic acids method (Erdogan et al., 2019). Firstly, the non-cellulosic substances in the waste jute fibers are removed through HCOOH at a concentration of 90%. Secondly, 35% H_2O_2 and CH_2O_3 are used to treat waste fibers to improve the delignification effect. Finally, the obtained material is bleached with H_2O_2 for 75 min at 60 °C. This method has the same advantages as the combined acid and alkali treatment. In addition, high energy planetary ball milling was also used to extract cellulose working under wet conditions (Baheti et al., 2014). Overall, the resulted products exhibit unique characteristics and can be used in different applications.

Table 2 compares the different methods of cellulose extraction. The double asymmetric centrifugation method is simple and continuous, but the characteristics of the processed lignin fibers limit its application. Alkaline treatment is the most commonly used chemical method to improve the crystallization of cellulose and partially remove lignin and hemicellulose. However, the low efficiency impedes its industrial application. In contrast, the combined treatment of acid and alkaline hydrolysis improves the yield of cellulose, and other extraction strategies can be combined to prepare the necessary materials, making it the most commonly used extraction method. Besides, the extraction methods based on organic acids and high-energy planetary ball mills have attracted the attention of researchers. Cellulose prepared by these methods has structural advantages and the significant application potential in oil-water separation materials, papermaking and industrial packaging. Overall, Table 2 summarizes the potential research directions and advantages for the extraction of bast cellulose and nanocellulose in the future, thus promoting the progress of the cellulose industry.

Adsorbent materials

Adsorption refers to using the surface of a substance to absorb molecules or ions in an ambient medium

Table 2 Comparison and discussion of different cellulose extraction methods

Method	Advantages	Disadvantages	Material form	Refs.
Double asymmetric centrifugation	Novel, simple and sustainable	Cannot be extracted from lignin fibers	Fibers	(Agate et al., 2020)
Alkaline and acidification process	Improve crystallinity; small size; non-toxic; high cell survival rate; high yield	Complicated procedures	Fibers	(Abraham et al., 2016)
Alkaline hydrolysis extraction method	Improve crystallinity; small particle size; remove lignin and hemicellulose	Low efficiency	Fibers	(Baksi et al., 2018)
Organic acid extraction method	Except for non-cellulose parts; high output	Generate acid solvent waste	Yarns	(Erdogan et al., 2019)
High energy planetary ball milling extraction method	Small particle size; simple and convenient	Long time	Fibers	(Baheti et al., 2014)

(Kuznetsova et al., 2018; Liu, 2015). Nowadays, the preparation methods of adsorbent materials mainly include carbonization (Gopinath et al., 2020), modification, and graft copolymerization.

Carbonization method

The uneven surface of the bast textiles can be considered the starting materials for the production of activated carbon, and its good adsorption performance is closely related to the content of cellulose and lignin in the bast fibers (Xu et al., 2016). Activated carbon is a micro-crystalline carbon with a black surface, large specific surface area and low bulk density (Pongener et al., 2017; Yang et al., 2011; Zhu et al., 2020), which is generated by high-temperature physical activation or chemical activation (Zhao et al., 2020). Presently, the preparation ways of activated carbon from the bast textiles waste include impregnation of the waste fibers for 1-2 h in the activator solution such as H_3PO_4, $(NH_4)_3PO_4$, KOH, or $ZnCl_2$, carbonization at a temperature ranging from 600 to 800 °C and time (Chen et al., 2018). For example, fibers can be pretreated with 17.5% NaOH and 0.7% $NaClO_2$ to remove hemicellulose and lignin, then carbonized in a tube furnace at 1000 °C for 30 min. Usually, the activator concentration is observed to influence the superficial area of activated carbon significantly. The higher the activator concentration, the lower the pyrolysis temperature, and the greater the surface area of activated carbon, which is an economically feasible adsorbent.

Senthilkumaar et al. (2010) and Ramrakhiani et al. (2022) coated H_2SO_4 on the surface of waste jute textiles. The resulting carbon product can be used to remove organophosphorus pesticides and Zn(II). After the experiment it was found that the adsorption properties of the carbonized bast textiles are mainly affected by the porosity and surface oxygen content, while the morphology was observed to have a negligible effect (Vukcevic et al., 2012).

Surface modification method

The limitations on the preparation area and long production cycles hinder the production of the adsorption materials by the carbonization method for industrial applications. Therefore, the appropriate surface modification methods are adopted to prepare better adsorbents. These methods include anionic azo dye modification, surface amination, and sulfonation reaction.

Flax fibers were modified by immersing in cetyltrimethylammonium bromide surfactant to prepare adsorbents, which exhibit the potential to be used to remove the anionic azo dyes from wastewater. Amino-functional modification is also one of the effective methods for preparing biological adsorption materials. The materials prepared by this method can effectively remove the pollutants and heavy metal ions from the effluents. In particular, the -NH_2 groups on the adsorption material induce a strong chelating characteristic towards the transition metals; thus, it can efficiently remove Cu^{2+} from the aqueous solution. Furthermore, Yang et al. (2018) also modified the waste jute with cationic polyacrylamide to raise the sludge dehydration capability, which is owing to the reason that the H_2O_2 can improve the dewatering performance of sludge by biopolymer degradation to release the bound water and lysis of sludge cells to release the intracellular water. Simultaneously, jute can form the holes and low compression filtration cakes together with cationic polyacrylamide and sludge particles to improve the dewatering performance, which shows high efficiency and thus indicates its potential in dewatered sludge treatment. On the other hand, sulfoethyl cellulose can be extracted and synthesized from the waste flax. The resulted product can be used to substitute for the heavy metal ion adsorbent and carboxymethyl cellulose (Kutsenko et al., 2007). In short, biomass adsorption material prepared by these methods exhibit an excellent ability to remove metal ions and sludges.

Graft copolymerization method

Graft copolymerization methods are often utilized to prepare the high-performance water absorbent materials, which refer to the reaction on the macromolecular chain for attaining chemical bonding to the appropriate branch or functional groups. The resulting product is called graft copolymer, which their performance depends on the composition, structure, length and number of the branches in the primary and branch chains.

Al-Mamun et al. (2010) prepared a selective ion adsorbent after the ultraviolet curing of jute yarns with $C_3H_4O_2$ and H_2SO_4 to remove Cu^{2+}. The materials prepared by graft copolymerization absorb metal ions in the wastewater and have high water absorption. A few studies employed the discarded bast yarns to develop super absorbent composites of flax residue-g-polyacrylic acid-acrylamide (Liu et al., 2014; Yu et al., 2015; Zhang et al., 2013). The obtained material exhibits effective water absorption and retention capacity in deionized water and distilled water, thus indicating their use in applications with high water absorption requirements, such as sanitary napkins. Meanwhile, waste ramie adsorbents with amphoteric/magnetic multi-structures could also be constructed by two different graft copolymerization methods. The resulting adsorbents' optimum adsorption capacities for methylene blue and Congo red were 195.9 mg/g and 147.7 mg/g, respectively. These two methods guided the preparation of highly efficient multi-structured adsorbents from waste ramie (Peng et al., 2022).

Table 3 tabulates the preparation methods and properties of the adsorbents developed from bast textiles waste. The

Table 3 Preparation methods and performances for adsorption materials

Material	Method	Activation/adsorbate	Material form	Refs.
Jute	Carbonization	H_3PO_4; $ZnCl_2/I_2$	Fibers	(Chen et al., 2018)
Jute	Modification	H_2O_2, cationic polyacrylamide/sewage sludge	Fibers	(Yang et al., 2018)
Flax	Graft copolymerization	Poly(acrylic acid)/water	Yarns	(Liu et al., 2014; Zhang et al., 2013)

commonly used activators in the carbonization process are H_2SO_4 and KOH, and the purpose is to enhance the pores on the surface of the material and reduce the energy loss. Almost all forms of bast textiles waste can be carbonized to produce absorbents. Different carbonization temperatures, durations, and activator concentrations affect the pore surface area. For instance, low pore surface area is obtained from a short duration and low carbonization temperature. However, the carbonization process is still the primary method for preparing the adsorbents for application in wastewater, dye adsorption and heavy metal treatment. As mentioned earlier, graft copolymerization is another proper chemical method for preparing adsorbents, whose precursors are usually the used yarns. Grafting with $C_3H_4O_2$ or other amides is widely utilized for heavy metal ion removal and wastewater treatment. Therefore, the summary provides a robust background for the preparation of the adsorbent materials.

Electrode materials

The commonly employed electrode materials are copper, graphite, tungsten copper alloy, steel, and cast iron (Yoon et al., 2013). Over the past two decades, agricultural waste biomass has become a promising raw material for carbon electrode preparation. Since biomass-derived carbon has the desired molecular structure for charge storage and transport, it is suitable for electrode materials.

Owing to the rich output of the bast fibers, their application for the preparation of anode materials for lithium-ion batteries has attracted much attention. $CuCl_2$ can activate the jute fibers to produce porous materials with high surface area, which can be used as the anode of lithium-ion batteries (Dou et al., 2019). The jute fibers were first immersed and stirred in $CuCl_2$ solution, then carbonized in an Ar atmosphere to prepare the porous carbon material. The acquired material reveals a remarkable specific charge capacity of 581 $mAh{\cdot}g^{-1}$ after 100 cycles at a current density of 0.2 A mm^{-2}. This fabrication method is expected to promote the application of the bast bio-carbon materials for use in lithium-ion batteries and sodium batteries, thus promoting the further development of the electrode materials.

Supercapacitors

Supercapacitor is an efficient energy storage device that exhibits the advantages of high power, long cycle life, wide working temperature range, fast charging and discharging, energy storage, minimal maintenance, and environmental protection (Elwakil et al., 2017; Parveen et al., 2021; Prabha et al., 2020). Therefore, numerous studies focused on developing new materials for high-performance supercapacitors such as porous carbon, carbon nanotubes, carbon derivatives, and graphene (Maksoud et al., 2020; Sundriyal et al., 2021).

Bast textiles waste has become an essential class of raw material for supercapacitors due to the unique porous structure of the resulted product. For example, Zequine et al. (2017) hydrothermally treated 1 g of jute fibers in 30 mL H_2SO_4 solution for 24 h and subsequently heated jute and KOH at 800 °C for 1 h under Ar atmosphere. The resulting product was used in the preparation of supercapacitors (Fig. 3a), and the carbonized jute exhibited a certain microporous structure (Fig. 3b). The supercapacitor resulted showed optimal flexibility and cycle stability, demonstrating the potential of carbonization to inexpensively recover the jute fibers and attain a flexible energy storage device with higher performance. Figure 3c shows the conversion of flax fabrics to porous carbon fiber sheets after activation with NH_3 and carbonization for use in supercapacitors (He et al., 2020). The structural diagram of the fabric surface is observed to be different during each stage, especially the pore structure that appears on the surface of the fabric after carbonization, which provides a theoretical basis for improving its conductivity. The optimum surface area obtained was up to 1152 $m^2{\cdot}g^{-1}$ with the maximum pore volume of 0.502 $cm^3{\cdot}g^{-1}$, thus indicating the effectiveness of the method in preparing the porous carbon fibers that can be directly used as a part of the supercapacitor. In addition to the mentioned methods for the production of supercapacitors, the carbides from the waste hemp fibers were successfully synthesized through KOH pre-treatment for subsequent assembling symmetric supercapacitors (Mijailović et al., 2017).

Table 4 summarizes the performance of various supercapacitors developed from bast textiles waste. The specific capacitance of supercapacitors assembled from the

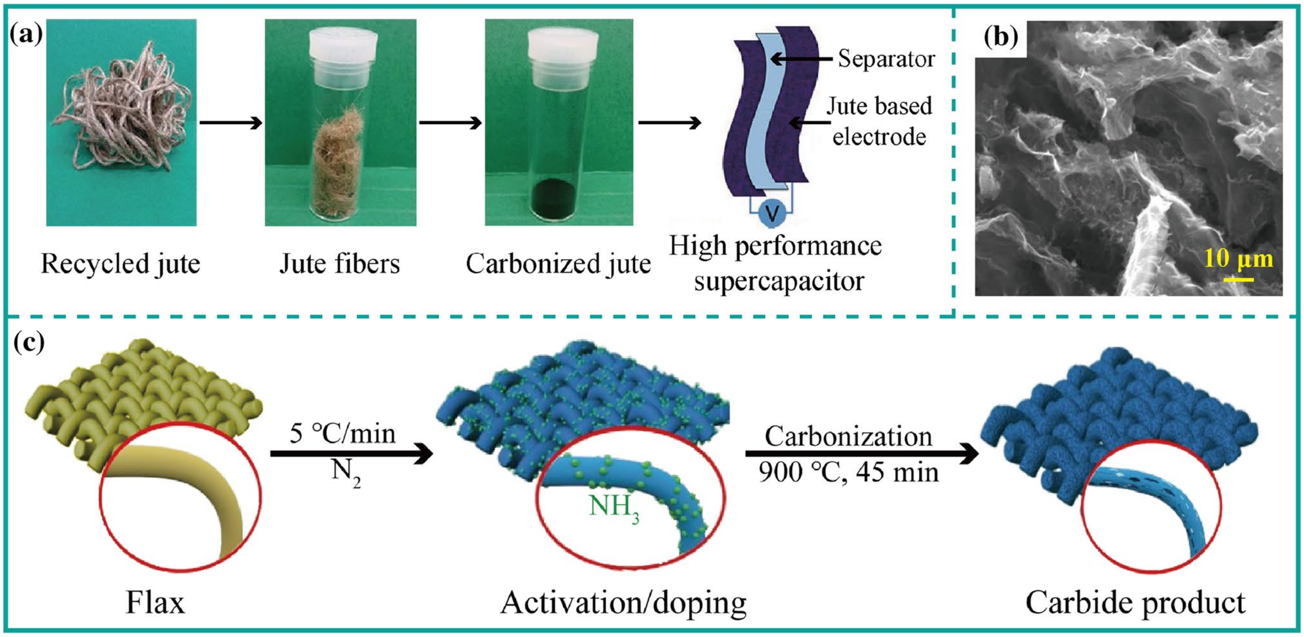

Fig. 3 Elementary diagrams of the preparation for supercapacitors. **a** Jute carbon material was produced by hydrothermal and chemical activation methods. Reprinted with permission of Springer Nature from Zequine et al. (2017). **b** Scanning electron microscope image of the carbonized jute. The material surface has a pore structure, which can improve its conductivity. Reprinted with permission of Springer Nature from Zequine et al. (2017). **c** The flexible porous carbon was prepared by the NH_3 activation method, which was used to assemble supercapacitors. Reprinted with permission of Elsevier from He et al. (2020)

Table 4 Comparison and analysis of performances for super-capacitors made of different bast textiles waste

Material	Electrolyte	SC max [specific capacitance $F{\cdot}g^{-1}$]	Stability [cycles]	Material form	Refs.
Hemp	1 M H_2SO_4	122	–	Fibers	(Mijailović et al., 2017)
Flax	6 M KOH	204.1	100% (3000)	Fabrics	(He et al., 2020)
Jute	3 M KOH	408	100% (5000)	Fibers	(Zequine et al., 2017)

carbonized waste bast fibers and nickel, with carbon nanotube as the electrode material, is noted to be 408 $F{\cdot}g^{-1}$, with the cycle stability reaching 100%, which indicates that the bast fibers have a significant application potential and development prospect in the preparation of supercapacitors. Furthermore, concerning the preparation method of the supercapacitors, the development of flexible wearable electronic textiles could be promoted.

Future research direction of bast textile wastes

Given the above recovery methods and applications, bast textile wastes can also be quickly, cheaply, and effectively recovered for the following aspects in the future:

(1) Preparation of filaments: Bast textiles waste is rich in cellulose, making them an essential raw material for the preparation of cellulose. The prepared cellulose can be made into cellulose filaments by wet spinning, and the filaments can be made into new clothes by the weaving process. In addition, cellulose filaments can also be combined with functional materials such as $BaTiO_3$, carbon nanotubes, and Mxene to synthesize products with good piezoelectricity and conductivity properties, promoting the development and application of cellulose filaments in the field of smart wearables.

(2) Preparation of composite reinforcements: Bast fibers wastes can be made into 3D needle felts by a low-cost non-woven process and then transformed into composites by resin transfer molding process. In addition, the thermoplastic fibers such as polypropylene fibers and polylactic acid fibers can also be combined with bast fibers wastes to make 3D needle felts, followed by the fabrication of the composites by the hot-pressing process. Moreover, the bast fibers wastes can also be used for spinning yarns, and the new fibers can be

added during the co-spinning process and subsequently woven, braided or stitched into 3D preforms for manufacturing composites.

(3) Preparation of catalyst: Most homogeneous catalysts are expensive and create pollution to the environment. In order to overcome these issues, the isomerization of homogeneous catalysts has attracted widespread attention in academia and industry. During this period, bast fibers with porous structures became a good choice for preparing the homogeneous catalyst.

Petit et al. (2018) prepared an isomerization catalyst through the functionalization of sisal-derived acid carbon and organometallic $[MoI_2(CO)_3(MeCN)_2]$ complex. The process uses H_2SO_4 as a medium to generate the sisal fiber material and subsequently synthesize the required catalyst with organometallic $[MoI_2(CO)_3(MeCN)_2]$ complex, as shown in Fig. 4a. The method converts the waste sisal fibers into technical products, which markedly improves the utilization value of these products. The succession experiments indicate that this material exhibits high working efficiency and recyclability. However, the metal loss may occur during the preparation process. Therefore, a new catalyst has been prepared by carbonizing the waste hemp textiles to obtain 3D porous carbon materials, then deposition the vertical MnO_2 wires (v-MnO_2) via a one-step hydrothermal method. The developed catalyst can be used for the glycolysis of $COC_6H_4COOCH_2CH_2O$ with a transition rate of up to 98%, which is expected to bring considerable economic benefits to the plastic recycling industry (Yang et al., 2017). Figure 4b, c presents the scanning electron microscope images of prepared 3D porous catalyst materials. The surface of the material presents a tubular structure with vertical deposition of MnO_2, thus indicating efficient recycling of the waste bast fibers in textile industries.

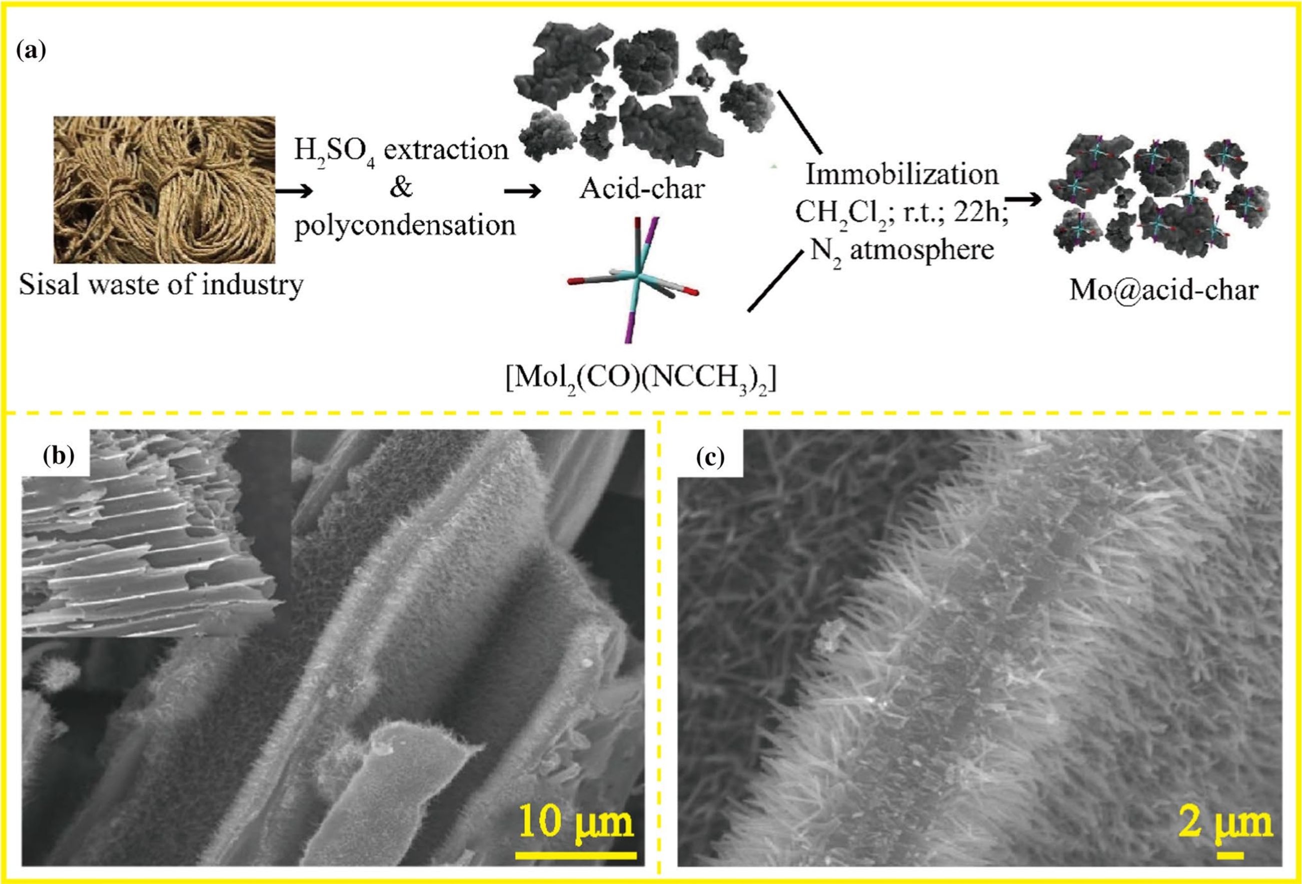

Fig. 4 Synthesis and scanning electron microscope images of catalysts prepared from bast textiles. **a** The steps of a catalyst prepared by acid char and metal-organic complex $[MoI_2(CO)_3(MeCN)_2]$ (Mo) functionalization. Reprinted with permission of John Wiley and Sons from Petit et al. (2018). **b** and **c** Scanning electron microscope images of 3D vertical MnO_2 wires/hemp-derived carbon (3D v-MnO_2/HDC) composite made by depositing v-MnO_2 at different magnifications. Reprinted with permission of Elsevier from Yang et al. (2017)

(4) Preparation of sensors: The sensor is equipment that converts the tested message into the required information based on definite conditions that can satisfy information propagation, machining, and memory. The flexibility and porous structure of bast textiles waste are a promising option for preparing strain sensors, gas sensors and biosensors.

He et al. (2019) prepared multifunctional reduced graphene oxide/linen fabrics through a reduction and inhalation filtration process as CH_4 gas sensors. Initially, the graphene oxide was converted into reduced graphene oxide using the Hummers' method, followed by the deposition of the reduced graphene oxide dispersion on the surface of the linen fabric to change its color to metallic black. The results indicate that the material has high sensitivity, reliability and feasibility and optimal moisture and air permeability during the synthesis process. This provides strong evidence that the material produced could be used as wearable intelligent devices in personal health care. A few studies also report high-permeable pressure sensors' development through the carbonization of knitted hemp fabrics (Liu et al., 2021). First, the hemp yarn is made into ideal knitted fabrics with a weft knitting machine. Subsequently, it is dried and carbonized in a tube furnace. The schematic of the graphite knitted hemp fabrics is shown in Fig. 5a. It can be observed that the knitted fabric becomes black, and the yarn becomes thinner after carbonization (Fig. 5b, c), which makes it possible to prepare the efficient pressure sensors. Finally, in order to study the conductivity of the graphite knitted hemp fabrics, they were cut into smaller rectangles (1.2×1 cm^2), and external wires and silver paste were connected at both sides. Meanwhile, this assembly can light up light emitting diodes (LEDs) in Fig. 5d. Furthermore, the unpackaged graphite knitted hemp fabrics have the unique advantage of high moisture permeability, showing great potential for use as a human-wearable device (Fig. 5e). After exploration, this material allows complete perspiration, which provides a new direction for the preparation of comfortable wearing pressure sensors.

On the other hand, untreated textiles can also be made into sensors by suction filtration or carbonization. This can then reasonably infer that bast textiles waste can be coated or impregnated with 2D materials, including reduced graphene oxide, carbon nanotubes, and Mxene, to prepare the piezoresistive sensors in the future for monitoring the human body motion. In short, the recycling value of bast textiles waste could be improved by transforming it into a sensor.

(5) Preparation of electrode materials: The bast textiles waste can also be made into electrode materials after activation with $CuCl_2$, KOH, or H_3PO_4, followed by

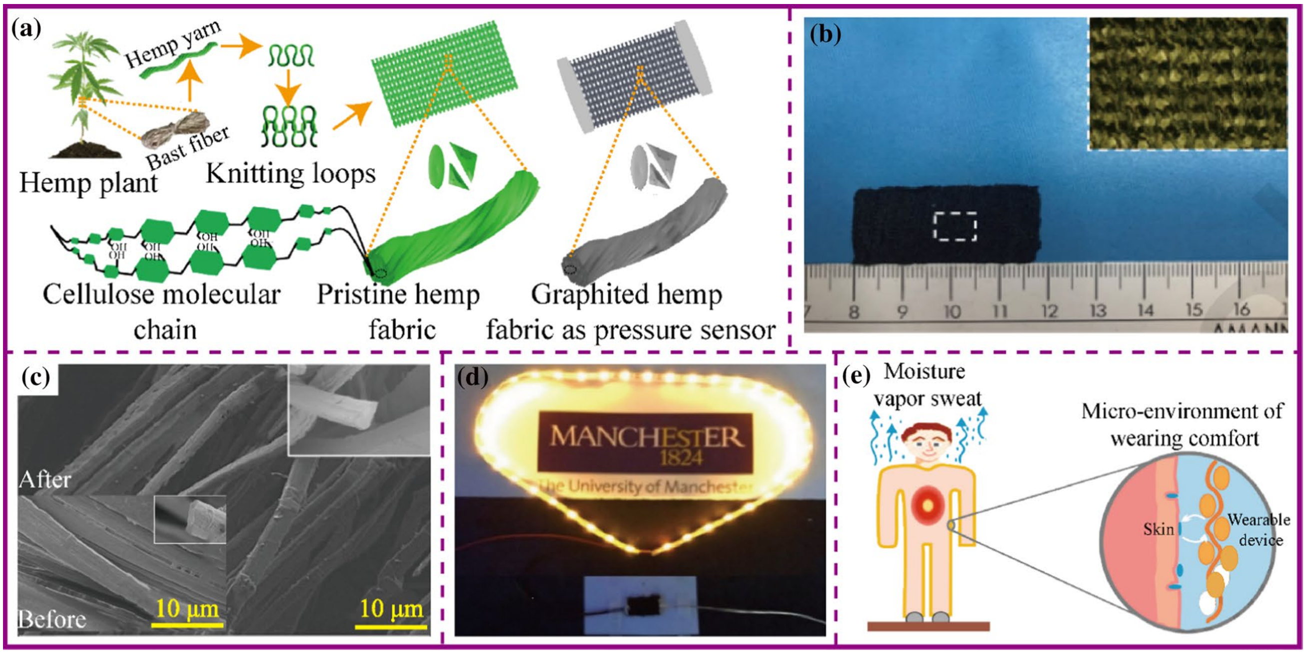

Fig. 5 Transformation of bast textiles into various sensors. **a**-**c** The production schematic diagram, picture and scanning electron microscope image of graphite knitted hemp fabrics. Reprinted with permission of Elsevier from Liu et al. (2021). **d** and **e** The conductivity of graphite knitted hemp fabrics and schematic diagram of wearables and environmental systems. Reprinted with permission of Elsevier from Liu et al. (2021)

carbonization. The resulted electrodes have the advantages of low-cost and easy production.

(6) Preparation of papers and battery diaphragms: The cellulose extracted from bast textiles waste can be made into battery diaphragms by electrospinning technology. This cellulose diaphragm has excellent immersion and high-temperature resistance, which has excellent potential for battery applications. At the same time, the wet laying process and the hot-pressing process can also be used to make cellulose into unique papers. This method has the merits of being green, fast and efficient, and the prepared paper has excellent washing resistance and tensile properties, making it a great option as packaging paper. In short, the suggested recycling methods improve the economic value of bast textiles waste and reveal the direction for recycling textiles waste.

(7) Recycling of thermal energy: Bast textiles waste that can no longer be reused can be converted into thermal energy for thermal power generation by burning. Research in this area can be strengthened in future studies to increase the variety of recycling methods for bast textiles waste.

Conclusion

The physical and chemical recycling methods of bast textiles waste and the applications of resulted products are reviewed. The waste bast fibers have the merits of moisture absorption, heat preservation and superior mechanical properties that can be used as raw materials for composite reinforcements. Moreover, high versatility of cellulose, nanocellulose and nanocrystalline cellulose can be extracted from waste bast fibers by double asymmetric centrifugation, alkaline, acid-base, and acidification. Meanwhile, the porous structure of bast textiles waste makes them a suitable raw material for the preparation of absorbents. After treatment by chemical activation and carbonization, it can be used for the adsorption of heavy metal ions, wastewater treatment, and gas sensors. Bast textiles waste is also useful for preparing electrode materials and supercapacitors with excellent conductivity and cycle stability. These characteristics allow the application of bast textiles waste in flexible electronic wearables. Although the studies on bast textiles waste have mainly been reported, the optimum recycling of bast textiles waste is scarcely reported, and the commercialization potential of the resulted product is still unknown. Therefore, the recycling process of bast textiles waste, the resulting products' properties, and the overall process's economic feasibility need to be further addressed.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest in this paper.

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Consent to participate Not applicable.

Consent for publication Not applicable.

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