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REVIEW

Recent Progress in Flax Fiber-Based Functional Composites

Hongbin Li[1,2] · Rongrong Tang[1] · Jiliang Dai[1] · Zixuan Wang[3] · Shiqi Meng[1] · Xiang Zhang[4] · Feng Cheng[2]

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Abstract

In recent years, flax fiber as a green and renewable resources have attracted considerable attention to be used as reinforcement in composites, using various technology. This review presents a summary of recent developments of flax fiber-based functional composites toward energy, biomedical, and environment. Firstly, we analyze the design and fabrication strategies, which are used for preparation of flax-based functional composites. The most promising applications of flax fiber-based composites are discussed subsequently. It is believed that flax fiber as a functional composites will play a crucial role in the field of energy, biomedical, and environment mainly attributed to its unique properties, such as specific mechanical properties, good biocompatibility, eco-friendliness, cost-effectiveness, and amenability to various functional design and manufacturing needs.

Keywords Flax fiber · Composite · Energy · Biomedical · Environment

Introduction

Flax (*Linum usitatissimum*), as an ancient natural fibers [1], has brought great changes to human life, enabling a wide range of applications across different disciplines such as literature, art, science, and engineering [2–4]. Figure 1 shows the structure of a single flax fiber which is composed of cellulose, lignin, hemicellulose, pectin, wax and a certain amount of water [5–8]. It is structured in two cell walls, a primary cell wall and a secondary cell wall containing three layers S1, S2 and S3, the most important being the S2 layer whose thickness is 5–15 µm. This layer consists mainly of cellulose embedded in a matrix of hemicellulose and pectin. Therefore, flax fiber itself is a composite material with cellulose microfibrillar as reinforcement, lignin and hemicelluloses as matrix.

Flax fiber is one of the first to be extracted for spinning and weaving into textiles [9]. In 5000 BC, flax fabric had been detected in graves of Egypt [10]. With the continuous progress of textile technology, the flax fiber products of making upholstery tow [11], insulating materials [12], yarn, and other textiles [13] were gradually developed. Flax fiber is also being used to produce other fibrous products such as car-door panels [14] and retaining mats [15]. In addition to the textile products mentioned above, flax fiber had recently attracted considerable attention as a renewable resources to improve the performance of the composites by various technique, specifically targeted towards in energy, biomedical, and environment field. Due to their special characteristics namely environmentally friendly, widely available, cost effective and biodegradable [16, 17], flax fiber also were selected to produce the automotive industries and infrastructures. In addition, the mechanical robustness of fibers is essential when they are considered as reinforcement in the fiber polymer composites. Compared with other natural and plant-based fibers, flax fiber-reinforced composites perform very similar to glass fiber-reinforced composites, in some terms. This might be generally attributed to the light weight and strong mechanical nature of this materials. Table 1 compares the mechanical properties of difference types of natural fibers and synthetic fibers. The flax fiber with specific tensile strength, as a flexible material, can be potentially an replaced

✉ Feng Cheng
chengfeng9004@126.com

[1] College of Light Industry and Textile, Qiqihar University, Qiqihar 161006, Heilongjiang, People's Republic of China

[2] MIIT Key Laboratory of Critical Materials Technology for New Energy Conversion and Storage, School of Chemistry and Chemical Engineering, Harbin Institute of Technology, Harbin 150001, People's Republic of China

[3] Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD 21287, USA

[4] National Center for International Joint Research of Micro-Nano Molding Technology, School of Mechanics and Safety Engineering, Zhengzhou University, Zhengzhou 450001, People's Republic of China

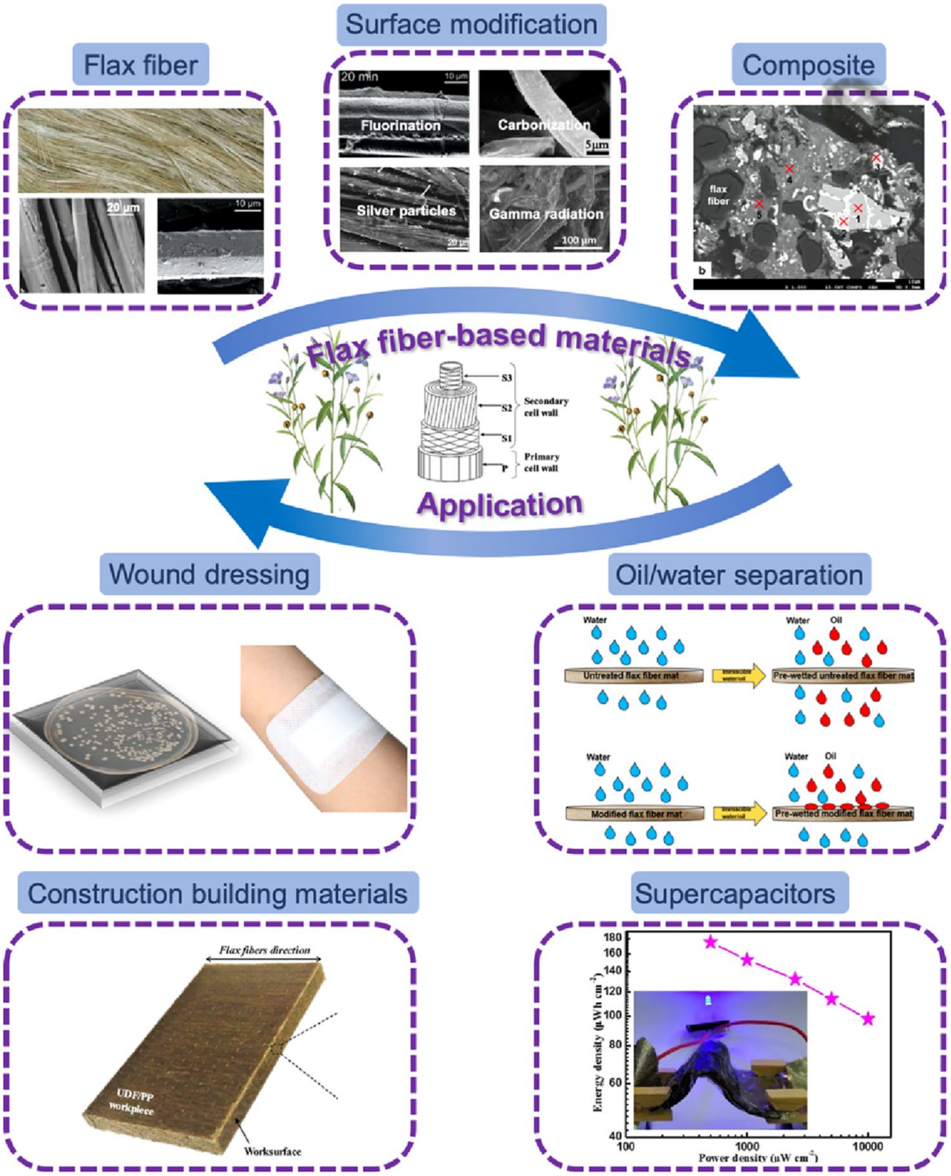

Fig. 1 Schematic of flax fiber-based function materials and its emerging applications in energy, biomedical, and environment at a low cost. Modification of physical and chemical properties of flax fiber allows the applications in wound healing, oil/water separation, buildingmaterials and supercapacitors. Images reproduced with permissions [20, 21, 30, 34–39]

for the conventional glass fiber, in many of different reinforced composites [18]. Modified flax fibers have been also selected to make the biocompatible the therapeutic apparels [19, 20]. In Paladini et al. work, they fabricated a natural flax-based wound dressing by combining silver nanoparticles, which show a desired antibacterial capability against *Staphylococcus aureus* and *Escherichia coli* [21].

Of note, with the crisis of energy and environment, flax fiber, as a renewable resource, have recently attracted considerable attention mainly attributed to its inexpensive and naturally abundanc, specifically in energy storage and conversation devices [26–29]. In He et al. work, the carbonization/activation technique were used to create a flexible porous high nitrogen-containing carbon fiber sheets which shown the excellent electrochemical performance in flexible supercapacitor [30]. Compared with traditional composites, natural fiber reinforced bio-based high-molecular polymer composites solve the issues of non-renewable energy and reduce other environmental impacts [31].

Recently a lot of efforts are put into analyzing the conventional applications of flax-based functional composite [32, 33]. However, on development of flax fiber-based functional composites for the purpose of energy, biomedical and environment applications has not been systematically

Table 1 Mechanical properties of natural fibers and synthetic fibers [22–25]

Fiber type	Density (g cm^{-3})	Elongation at break (%)	Tensile strength (MPa)	Tensile modulus (GPa)
Ramie	1.5	3.6–3.8	400–938	44–128
Sisal	1.45	2.0–2.5	511–700	3.0–98
Flax	1.5	1.4–1.5	345–1500	10–80
Jute	1.3–1.45	1.5–1.8	270–900	10–30
Cotton	1.5–1.6	7.0–8.0	287–597	2.5–12.6
Kenaf	/	2.7	427–519	23.1–27.1
Hemp	1.48	1.6	270–900	20–70
Coir	1.15	15–40	131–175	4–6
E-glass	2.5	2.5	2000–3500	70
S-glass	2.5	2.8	4570	86
Aramid	1.4	3.3–3.7	3000–3150	63–67
Carbon	1.4	1.4–1.8	4000	230–240

discussed in detail. Understanding the fundamental properties and corresponding function of flax-based composites is a essential task, prior to design and manufacturing of any related device or component. The objective of this review is to explore the natural fiber made from flax and their applications in development of different functional composites and products (as shown in Fig. 1). This review will inspire research in flax-based functional composite and inspire new ideas to explore value-added high-value utilization of flax.

Modification of Flax Fiber for Functional Composites

Flax fiber is an interesting alternative to the conventional fiber materials (e.g., cotton, glass, and synthetic fiber) because of its excellent mechanical properties [40]. Flax fibers, as a kind of biomass composites, have a variable biopolymer composition, which contains various percentages of cellulose, hemicellulose, lignin and pectin et al. [41, 42]. However, due to higher water absorption of flax fiber, it is not a suitable material for bonding with polymer matrix [43]. Therefore, the flax fibers should be modified using various technologies, to be improved in interfacial adhesion with the polymeric matric. So far tens of chemicals and treatments methods have been adopted to this aim; alkali [44, 45], silane [46, 47] and, acetylation [48] treatment, as well as the physical methods (plasma exposure [49], grinding and ball milling [50], and irradiation [51] are of the most typical technologies to this aim.

Alkali Treatment

In order to remove hemicelluloses and lignin, the alkaline solution is always selected to remove the impurities, and enhance the mechanical and adsorption properties of flax fiber [52]. In Samyn et al. work, an alkaline pre-treatment with sodium hydroxide were done in order to remove the impurities of the flax fiber and to enhance the formation of -OH groups on its surface [53]. This pre-treatment could significantly improve the adsorption performance of the fiber and also favour the grafting of silane into or onto the surface of the flax fiber.

Silane Treatment

In order to further improve the interface adhesion between fiber and polymer matrix, coupling agents can be used as an effective strategy. Silane coupling agents have been considered as of the most effective binders which have been widely applied in natural fiber/polymer composites [54]. In a report from Fathi et al. carboxyl groups (COOH) was grafted on the surface of flax fiber. Alcoholic (OH) groups were successfully converted by using TEMPO oxidation technology. Then the flax fibers were soaked in the neat silane for 0.5 h at room temperature. As concluded from results the TEMPO oxidation technique enhances the bonding efficiency of silane groups onto the fiber surface. The surface modification of flax fiber also significantly enhanced compatibility between the flax fibers and the bio-epoxy resin.

Acetylation Treatment

Moreover, acetylating process and microwave energy were also used to enhance the sorption properties of flax fiber in the application of oil–water separation [48]. In their work, the flax fiber was immersed into the mixture of acetylating liquid solution or treated by a microwave radiation in a microwave oven. Their results demonstrate that the modified flax fibers by the acetylating process have a remarkable hydrophobic nature and a well formed porous structure, mainly attributed to its interaction with the acid anhydride group, rendered by ethanoic anhydride. Also, the microwave effect can enhance the formation of porous structure and, therefore improves the potential of the oil sorption.

Plasma Treatment

On the other hand, the plasma method are considered as a kind of dry and clean technique compared with the methods mentioned above [49]. The plasma method is a physical procedure to modify the fiber surface by forming strong bonds between new functional groups of flax fiber and polymer matrix under atmospheric condition. In Bozaci et al. work, argon and air atmospheric pressure plasma systems with different plasma powers were used to improve the interfacial adhesion performance between flax fiber and polymer matrix [49]. After both plasma treatments, the new functional group (O–C=O) were proved to be generated on the flax fiber surface, and the surface of flax fiber showed more roughness which is a proof of better adhesion between air plasma-treated flax fiber and unsaturated polyester.

Grinding and Ball Milling

In addition, flax fibers can be processed into desiccant material to form a bio-desiccant coating for an air-to-air exchanger via the ball-milled and mechanically ground technology [50]. The ball-milled flax fibers were screened to improve the size and uniformity (≤ 125 μm), using a 120 mesh US standard sieve. These efforts proved that ball-milled flax fibers-coated exchanger had latent effectiveness values of ~ 10, which is around 40% greater than the similar products, coated with starch particles and silica gel. The enhanced surface and textural properties, along with the complex compositional structure of flax fibers, and its greater propensity to swell in water, account for the improved performance over starch particles. Thus, flax fibers can be considered as an alternative cost-effective, biodegradable, and sustainable bio-desiccant in buildings.

Irradiation Treatment

For improving the interfacial adhesion between flax fiber and polymer matrices, Youssef et al. has designed and fabricated a low density polyethylene/flax bio-composites by combining chemical modification and radiation-induced grafting strategies [34]. The flax fibers treated with octadecylphosphonic acid were irradiated by using a ^{60}Co source with a 10 kGy of dose at room temperature. Their results demonstrated that the uniaxial tensile performances of the bio-composites are enhanced which maybe further enhanced by electron-induced reactive processing. In another research, gamma irradiation also was selected to enhance the mechanical performance and thermal resistance of polylactic acid/flax composites in the presence of cross-linking promoter [51].

Finally, functional nanoparticles have been proven to be an effective materials for fabricating multiscale composites with the better mechanical and interfacial properties [55, 56]. In Wang et al. work, a flax fiber sheet was grafted with multiwalled carbon nanotubes, and nano-TiO_2 particles [57]. Then, the flax composites were obtained with the modified flax fiber sheets and epoxy resin by the hand lay-up method. The results show that the multiwalled carbon nanotubes can significantly improve the tensile strength and interlaminar shear strength of flax composites than those grafted with the same content of nano-TiO_2 particles.

In a word, for the modification of flax fiber as a functional composite, the interfacial adhesion of flax fiber with most polymeric matric in composite are a critical factor, which determines the mechanical property in practical application. Based on all these reasons, different fabricate technique can lead to the flax fiber-based functional composite with various mechanical resistivities, to be applicable in different field.

Fabrication of the Flax Fiber-Based Functional Composites

Flax fibers, as a functional material, can exist in a variety of forms in composites, not just monofilaments [58]. Monofilament fibers are further processed into mats [35], rovings [59], yarns [60], and fabrics [61] in composites. Therefore, the flax fiber-based functional composites can be prepared with different methods such as, coating [62], carbonization [28], textile technology [63], 3D printing [64], and compression molding [65]. The above mentioned techniques can be also adopted to compose various flax fiber-based functional materials, for numerous applications inenergy [26], biomedical [66, 67], and environment applications [68].

Coating

To obtain flax-based antibacterial materials, the flax fabrics are usually coated with bioactive molecule, antimicrobial agent or nanoparticles, which is a relatively mature technique for fabricating the antimicrobial flax-based materials. The coating system as a template was selected for in situ adhesion or deposit onto/into the flax fabrics. Then, flax-based antibacterial textiles and webs can be fabricated through various coating solution, such as hydrogel [62], solution loaded nanoparticles [21] through different curing strategies. Silver nanophases, as an effective antibacterial agent, always are used for biomedical applications and wound healing. In a research conducted by Paladini et al. the silver-doped hydrogel were formed on the surface of the flax fabrics [62]. In a similar work, silver coatings were adhered onto the flax textile via in situ photo-reduction [21]. These results manifest that the silver photo-deposition strategy can be easily translated from laboratory to large scale, without influencing the performance of the silver coating deposited. Finally application of silver in deposition treatment provides a promising feature of potential biomedical applications in for wound dressings and healing purposses.

Carbonization

Flax fiber, as a cellulose based material, has a unique 3D microporous structure, a superior electrical conductivity and chemical resistance and is counted as a disposable compound. Unlikely coating, the carbonization technique was carried out in a tube furnace at a higher temperature for certain amount of time with argon or N_2 as a carrier gas. Then, carbon-based materials with good electrical conductivity, large-scale, and low-cost production capability can be achieved from the flax fiber, via through carbonization. In a work reported by Zhang et al. the carbonized flax fabric with macro-pores structure was selected to create nano-structural materials, along with an in situ growing of CNTs micropores and mesopores for ion transport application (Fig. 2A) [28]. Using flax fabric directly instead of cellulose fibers can significantly avoid dispersion issues and make no concerns about polymer binding during processing, thus provides a higher electrical conductivity and chemical stability.

Textile Technology

Compared to the synthetic fibers, flax fibers demonstrate a higher mechanical endurance demonstrate [69]. Textile technology, such as micro-braiding [70] and co-wrapping [71], have been developed to produce similar hybrid yarn structure (Fig. 2B). The micro-braided yarns were fabricated by a tubular braiding loom with several spindles that hold bobbins with braider filaments. The co-wrapped yarns were fabricated by a hollow spindle spinning loom. In a study by Zhai et al. the micro-braided (Fig. 2B-i) and co-wrapped flax/polypropylene (PP) yarns (Fig. 2B-ii) were obtained by varying different PP parameters (PP braiding angles and PP wrapping turns, respectively) [63]. In general, micro-braided and co-wrapping techniques open up a broad prospect for the design and fabricate thermoplastic bio-composites.

3D Printing

More recently, studies on substitution of flax fiber for synthetic fiber in composite materials has attracted extensive attention in academic circles [72, 73]. Recent progress in 3D printing enables more advanced design and manufacture of fiber-embedded composites [74, 75]. In a report from Jiang et al. the short flax elastomer composites have been fabricated by 3D printing (Fig. 2C) [19]. Specifically, in 3D printing process, the liquid-phase “ink” is dispensed via various nozzles under controlled flow rates and deposited along digitally defined paths to build 3D structures by a layer-by-layer strategy. Results show that the short flax fibers can obviously improve the mechanical property of the composite. Their method extends the design and structural complexity for elastomer composites with natural fiber-embedded. In addition, Jiang et al. also report the development of printable highly transparent flax fiber-reinforced composites [64]. Their excellent printability in 3D printing processes allowed fabrication of composite structures using plant-based materials. The findings of this work demonstrate a novel and sustainable method to build engineer transparent composites with excellent mechanical and processing characteristics for functional devices, such as wearable electronics and soft robotics in multiplex geometries.

Compression Molding

Compression molding is known as the oldest technology for fiber-based composites [76, 77]. Recently, the need for mass production of the robust and, high stiffness and lightweight composites, especially for automotive applications, has again brought up this process to the center of attention. In Ismail et al. work, the wet lay-up strategy was selected to make the hybrid composites by high pressure curing for 24 h (Fig. 2D) [65]. To withstand a higher impact on synthetic laminate, each panel should contain six layers of fibers. Le et al. fabricated a moisture-induced self-shaping flax-reinforced polypropylene bio-composite actuator by hot-press using the film stacking technique, combining different numbers of active

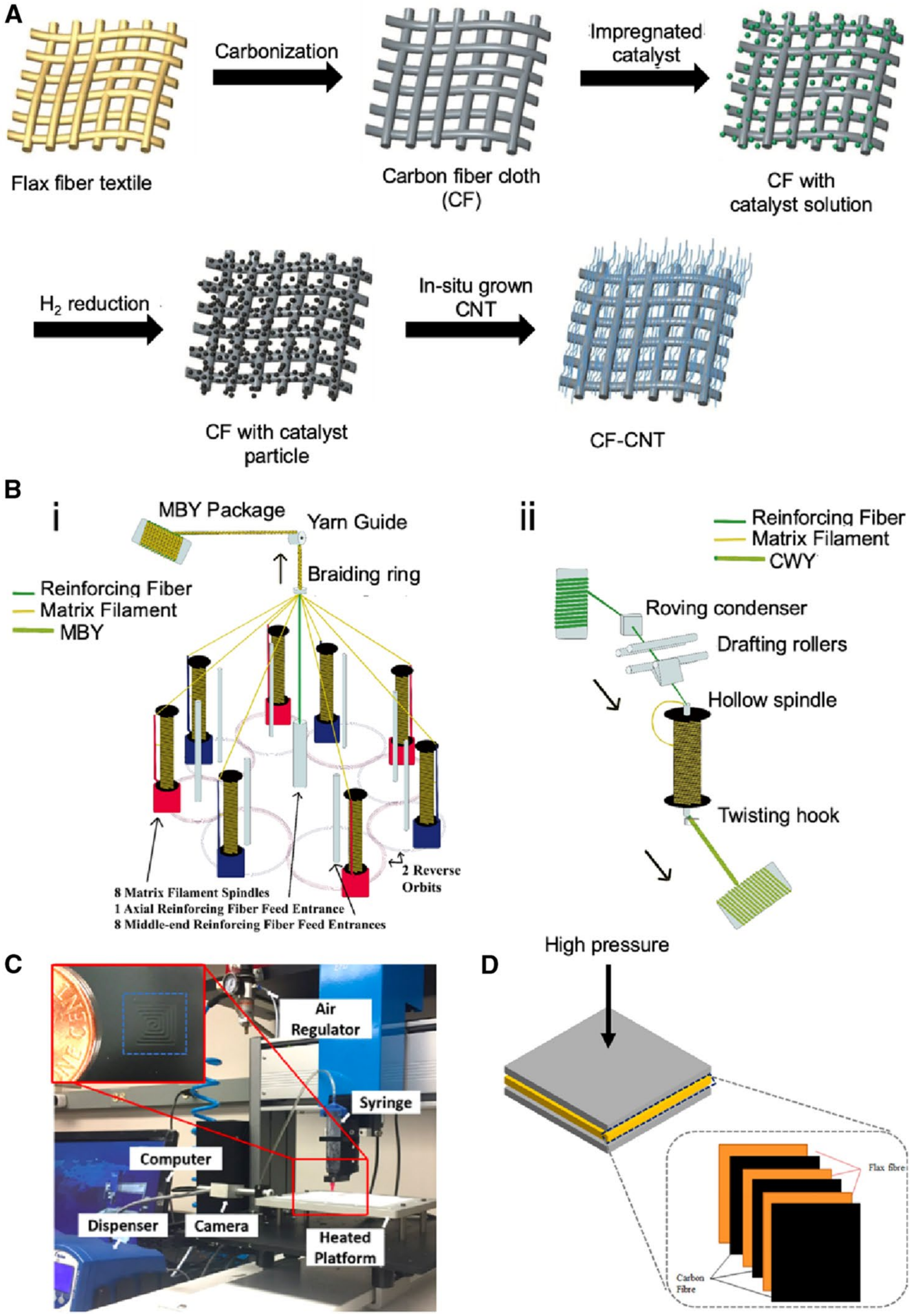

Fig. 2 Fabrication of flax fiber-based functional composite. **A** Carbonization. Images reproduced with permission [28]. **B** Textile technology, **i** micro-braiding and **ii** co-wrapping techniques). Images reproduced with permission [63]. **C** 3D printing. Images reproduced with permission [64]. **D** Compression molding. Images reproduced with permission [65]

and passive layers [78]. Their results indicate that moisture-induced bending actuation can be obtain via the water uptake and swelling of flax fiber, which can be considered as a driving force. Moreover, moisture induced bio-composite actuators withstand immersion. As a result, they keep their flexure shape without suffering from significant stress relaxation.

Application of Flax Fiber-Based Functional Composites

Flax fibers as reinforcement have been reported widely in composition with various polymers [79–82]. Due to their lighter weight and higher mechanical properties, flax fiber-reinforced composites are similar to glass fiber-reinforced composites, in terms of properties and functionality. In addition, as a general behavior for every reinforced composite the size distribution and physical properties of the filler materials (here flax) determines the strength and the functionality of the final product. Flax fiber-based composites are flexible, so can be easily folded or bended. This behavior makes them a potential candidate for the bonding polymer matrix which should be essentially strong but pliable. Thanks to all these favorite features, flax fiber-based composites have been increasingly utilized as a powerful platform for developing many different types of functional composites.

Biomedical

Unremitting and intense wounds are able to be rapidly tainted and sullied by organism like microbe and multidrug resistant bacteria. Bacteria uses the nutrients and oxygen existed in the host cells. This a very typical and obvious reason for prolonging the wound healing. Toxins and enzymes secreted from the wound site also trigger a bioburden [83, 84]. Paladini et al. fabricated, wound-dressing biomaterials by storing flax substrates with a hydrogel inserted into silver particles [62]. Presence of the di-phenylalanine hydrogel provides an efficient matrix to entrap the particles, leading to the promotion of a rapid wound healing without drying the

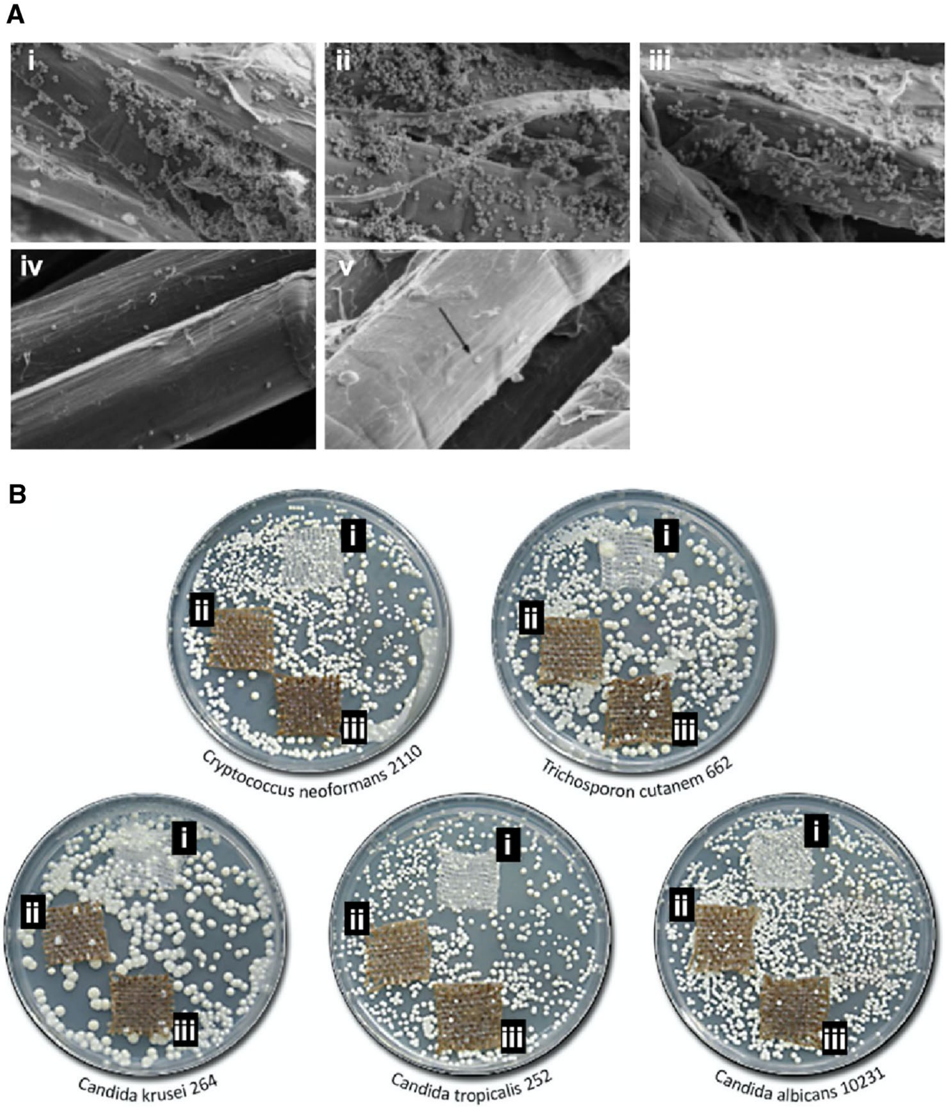

Fig. 3 Flax fiber-based functional composite for antimicrobial application. **A** Scanning electron micrograph of the flax. **i** Untreated group, **ii** Fmoc-F_2 coated group, **iii** coating with Fmoc-F_2 + 0.01 wt% Ag, **iv** coating with F_{moc}-F_2 + 0.1 wt% Ag, **v** coating with Fmoc-F_2 + 2 wt% Ag. Images reproduced with permission [62]. **B** Surface inhibition of growth of fungal colonies on cotton fabric (**i**), flax fabric-M type (**ii**), and the control (**iii**). Images reproduced with permission [20]

wound. Specifically, silver nanoparticles have shown great antimicrobial activity towards viruses [85, 86], fungi and multidrug resistant bacteria [87, 88] due to the high surface to volume ratio [89]. Figure 3A shows that a complete inhibition in bacterial adhesion occurs for a group containing 2 wt% Ag. On the other hand, there is no evidence on formation of a biofilm in a group with 0.1 wt% of Ag. However, the coated group without silver has formed biofilms on the surface of fibers.

In another research polyhydroxybutyrate (PHB) synthesis genes of ralstonia eutropha were combined with flax genomes [20]. This synthesized PHB advances the proliferation of human fibroblast and has antimicrobial activity in vitro (Fig. 3B). Due to the great property of PHB-fabric, it has been proved that the novel fabrication method is successful in preclinical trials. In conclusion, the natural texture of the flax plants that produces PHB, let to desired achievements in wound dressing and was occasionally used to prevent chronic skin ulcers. It is worth mentioning that a small amount of flex can create a huge amounts of fibers, so the expenses of wounds treatment is impressively controlled. However, as of yet, the mechanism and the reason of the antimicrobial nature of flax fiber has not been fully recognized, at the molecular level. Presumably, this effect might be due to a combined action of many components, found in flax fiber such as phenolics, terpenoids, sugars and fatty acids.

Supercapacitors

World widely, there is a rapid increasing demand for eco-friendly and renewable materials, as the current energy resources are substantially harmful to public health, wildlife and global warming emissions [90, 91]. He et al. have selected an inexpensive woven textile made of natural flax fibers, as the raw material for preparation of binder-free and adaptable component of supercapacitors (Fig. 4A-i) [92]. The specific capacitance of the carbon fiber cloth directly carbonized from the linen fabric is fairly low (0.78 F g^{-1}), but the relaxation time of the electrode (39.1 m s^{-1}) is short and shows a great stability, maintaining almost the whole capacitance. The specific capacitance of MCFC1 can reach 683.73 F g^{-1} at 2 A g^{-1} and still retains 269.04 F g^{-1} at 300 A g^{-1}, which more confirms that the biomass-derived flexible carbon cloth, coated with MnO_2 nanosheets has an excellent capacitance properties. (Fig. 4A-ii). This low-cost, environmentally friendly, and convenient manufacturing process may contribute to the advancement of energy storage devices in the future.

Zhang et al. reported a 'supercapacitor electrode' about the application of flax fiber textiles in flexible energy storage devices (Fig. 4B) [28], where a CF-CNT hybrid with a porous hierarchical 3D structure was prepared, in which the size of pores (micro pores versus meso pores) could be adjusted by changing the content of CNTs. The hybrids show great a performance in electrochemical properties, exhibiting high cycling retention and a capacitance of 191 F g^{-1} at 0.1 A g^{-1}. Owing to an entirely an layered structure of carbon, it is possible to manufacture the supercapacitors with a compelling flexibility, cost effectiveness and self-supporting structure.

Moreover, by controlling the activation level of NH_3, a flexible, porous and high nitrogen-containing carbon fiber sheet could be prepared, out of biomass flax (Fig. 4C-i) [30]. In this process NH_3 acts as both a nitrogen source, and activator. The assembled carbon fiber sheets activated by NH_3 shows outstanding flexibility, indicating the efficacy of NH_3 in treatment of biomass. Besides, the assembled symmetric and flexible cells demonstrate exceptional energy densities up to 174.7, 97.7 μWh cm^{-2} respectively occurring at power densities of 500, 10,000 μW cm^{-2} (Fig. 4C-ii). The porous structure of N-doped carbonized flax sheet also creates a great potential for being applicable in flexible energy storage devices.

However, eco-friendly synthesis and moderate activation protocols for enhancing their electrochemical performances are still challenging.

Oil/Water Separation

Separating the oil and water is a global challenge due to the severe water contamination caused by oil spill accidents, food, textile, and petrochemical industries [93–95]. Flax fiber contains a certain amount of cellulose, leading to the hydrophilicity [96]. Still, oil can be soaked up on the fiber surface, through the lumen, wax and lignin.

To overcome this issue, flax fibers were fabricated to separate immiscible water and oil [37]. To this aim flex fibers were used with plasma modified of poly (acrylic acid) (PAA) and self-assembled TiO_2 nanoparticles (Fig. 5A). Plasma treatment imposed a significant change in surface energy, as the characterized contact angle decreased toward water and increased toward oil. This manipulation of surface energy could drive a significant level of separation. The modified flax fiber has a stable separation performance between oil and water, in a salty and alkaline media, in multiple cycles (Fig. 5B), and even could behave as an oil barrier with great wettability.

The acetylation and microwave vitality can also modify the flax fibers, resulting in a promising future of oil spill cleaning [48]. The interaction with the anhydride groups of acetic anhydrides creates a hydrophobic nature on the surface and forms a porous structure hydrophobicity and porosity. Acetylation promotes the absorption, making fibers competitive with other synthetic fibers. Acetylated fibers demonstrate an excellent oil sorption performance (24.54 g g^{-1}), compared with both original(13.75 g g^{-1}) and microwave treated fibers (17.42 g g^{-1}), with exothermic absorption behavior. The rapid removal, biodegradable, costless, and great sorption potential of acetylated fibers make it a really suitable alternative adsorbent for oils from oil/water systems.

In another work, the flax cellulose nanofibrils obtained by using chemical modification on the commercial filter papers as a surface barrier for oil/water preparation [42]. Result demonstrates that the pristine filter paper cannot separate the oil/water mixture, mainly due to the large pore size, however, the flax cellulose nanofibrils modified filter paper can effectively separate the oil/water mixture (Fig. 5C). The modified filter paper can effectively separate the oil/water mixture, and the separation efficiency of FF8-CNF grafted filter paper for castor oil and pump oil are reported 95.3%, 92.2%, respectively (Fig. 5D). However, there is no significant differences in separation efficiency of FF3-CNF, FF8-CNF and FF13-CNF modified filter paper, perhaps because the CNF modified filter paper are basically excellent in a separation of for oil/water mixture.

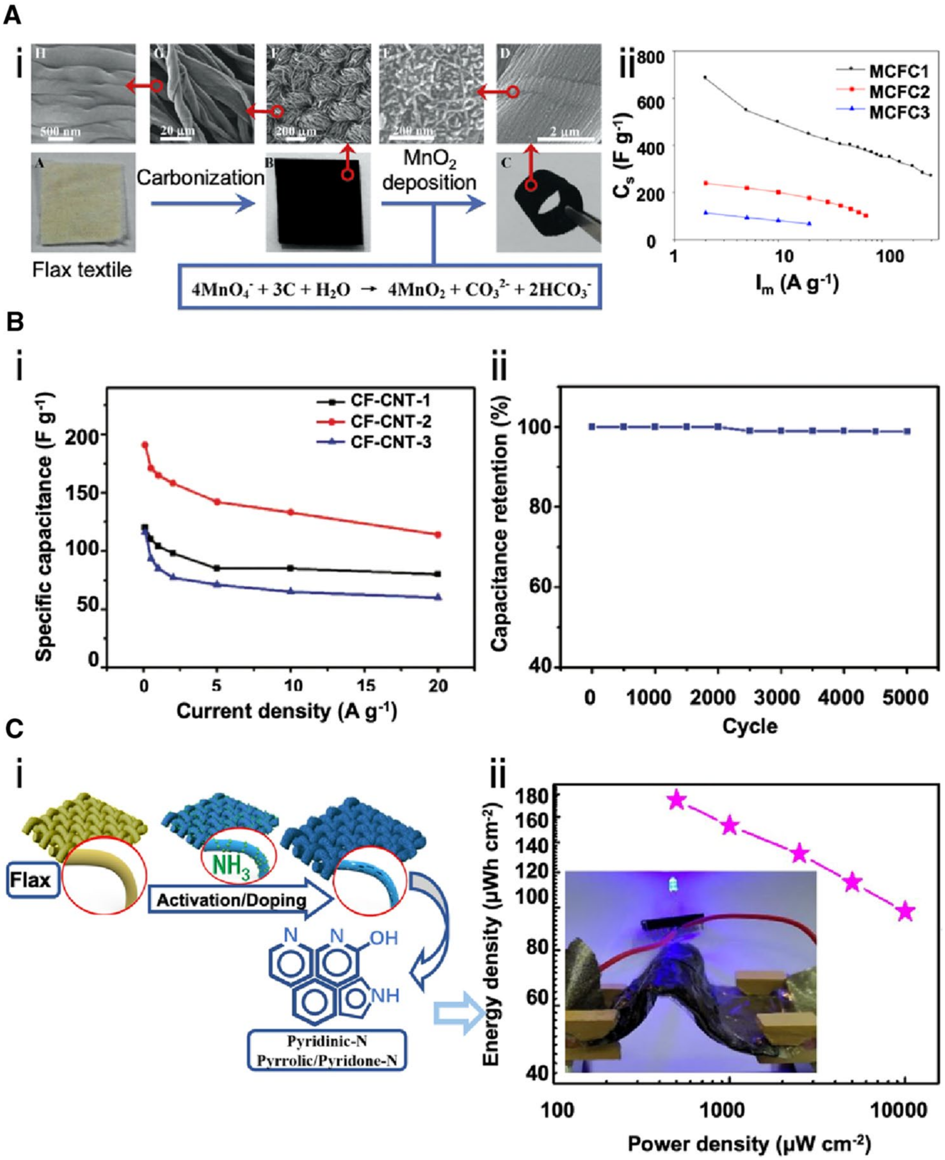

Fig. 4 Flax fiber -based functional composite for supercapacitors. **A** Schematic of the carbon/MnO_2 cloth hybrids preparation (**i**) and capacitance performances at different current densities (**ii**). Images reproduced with permission [92]. **B** The specific capacitance versus current density (**i**) and the last cycles of charge–discharge curves CF-CNT-2) (**ii**). Images reproduced with permission [28]. **C** NH_3 activation/doping process parameters (**i**) and high energy and power density (**ii**). Images reproduced with permission [30]

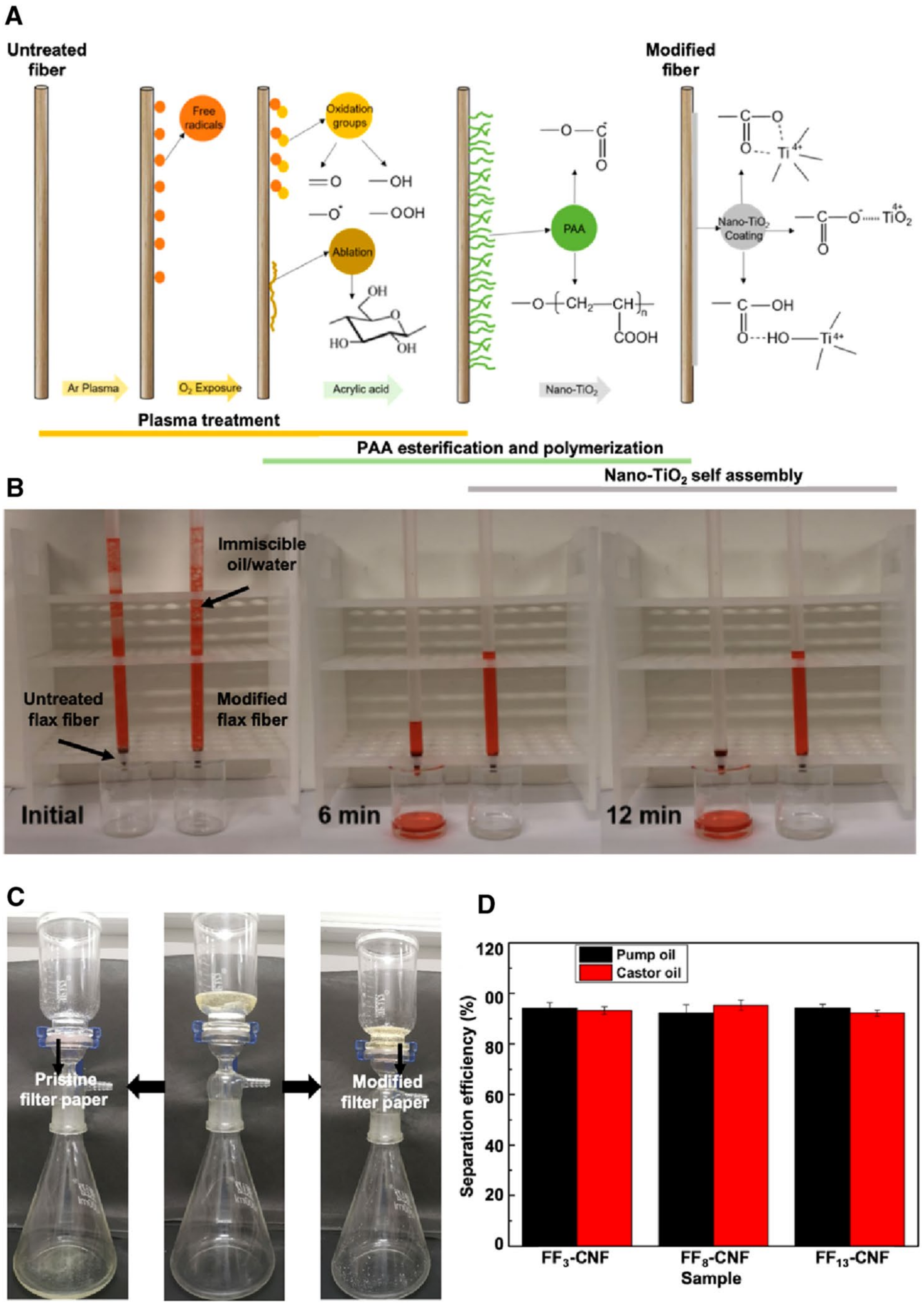

Fig. 5 Flax fiber-based functional composite for oil/water separation. **A**, **B** Modification process and mechanism of flax fiber and the oil/water separation performance between untreated and modified flax fiber. Images reproduced with permission [37]. **C**, **D** The separation performance between pristine filter paper and flax cellulose nanofibrils modified filter paper. Images reproduced with permission [42]

However, it is found that the interface between the flax fiber and composite matrix changes in by aging in wet environments. This deformation directly affects the tensile properties of the composites, so leaves a fundamental challenges for further observation and analysis.

Building Materials

Flax fibers as reinforcement agent or filler are known to be superior versus many of the other counterparts, on account of their natural origin, biodegradability, low density and high stiffness [97, 98], while they are finding novel applications in management of energy resources and consumptions [99–101]. Yan et al. examined fabricated a flax texture fortified epoxy composite tube as a restriction used with concerete [102]. Prefabricated linen/epoxy composite pipes are also lightweight permanent formworks for fresh concrete, and protect the wrapped concrete from harsh environments, like deicing salt. There are more researches focusing on the applications of flax fiber as various structural elements, e.g. PLLA/flax mat/balsa bio-sandwich during transportation [103] and flax composite pipe wrapped concrete as bridge piers [104].

Flax fiber belongs to cellulose and burns very easily. Therefore, to be used in to construction and automobile industry, it is necessary to increase the ignition point of the materials or give them a certain amount of flame-retardant properties. With the continuous improvement of people's safety awareness, fire-resistant and flame retardant materials will become the hot and difficult points in the future material research and study.

Conclusions and Perspectives

With its unique advantages, flax fiber has become a promising functional material. Such advantages include the hydrophilicity, sustainable, low-cost and mechanical strength provided by the flax fibers. The highly mechanical strength of flax fiber makes it an effective reinforcement in composite, and promise the next-generation of materials for application in energy, biomedical, and environment societies. More importantly, flax fiber-based composites are made by facile techniques such as coating, carbonization, textile technology, 3D printing, and compression moulding, and are applicable in plenty of fields and devices, for instance, wound-dressing, supercapacitors, oil/water separation or building materials.

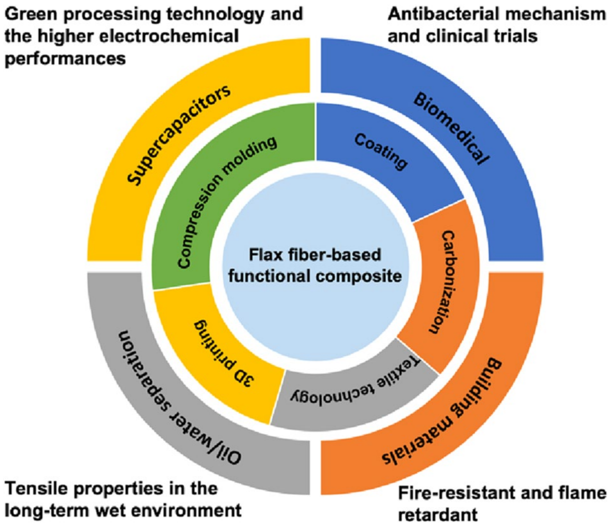

Fig. 6 The present problems flax fiber-based functional composite in the field of energy, biomedical, and environment

However, the limitations associated with these functional composites are not none (Fig. 6). As a medical wound dressing, further clinical trials are needed to verify the biosafety and efficacy of flax fiber-based functional composite. Flax fibers are incompatible as a reinforcing agent for composite materials, resulting in unfavorable fiber/matrix interfacial bonding and reduced adhesion between the fiber and the polymer matrix. Chemical modifications of the matrix and fiber is a solution to some existing challenges, and enhance the mechanical properties of flax fiber composites. Modification are implemented using both chemical and physical strategies. Grafting a chemical binding groups on the surface of the flex fibers can improve the interfacial interactions between flax fiber and polymer matrix. Moreover, adopting an appropriate manufacturing processes and physical/chemical modifications can improve the mechanical properties of flax composites. However, the high initial cost of some strategies is a serious drawback for commercialization. Further consideration needs to be given to faster, cheaper and environmentally friendly methods of modification.

In summary, flax fiber-based functional composite have been used in the fields of energy, biomedical, and environment. due to their numerous advantages mentioned above. Fabrication of flax fiber-based functional composite for new applications may greatly benefit our society. Future work on flax fiber-based composites should be focused on understanding the environmental assessment, durability, further improving the mechanical properties. Additionally, novel manufacturing processes and surface modification methods should be further developed.

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Declarations

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Hongbin Li is currently studying for his doctor's degree in Harbin Institute of Technology since 2017. He received his Master's degree from Donghua University in 2012. He is a Lecturer of Qiqihar University now. From 2018 to 2019 he worked as a visiting scholar at Harvard Medical School. His research interest is cellulose and fiber-based biomedical materials and functional modification of flax fiber.

Feng Cheng received her PhD degree in chemical engineering and technology at Harbin Institute of Technology in 2020. Then, she joined Harbin Institute of Technology as a lecturer in 2020. From 2018 to 2019 she worked as a visiting scholar at Harvard University. Her research is focused on the preparation of chitosan and cellulose based functional hydrogel materials for wound healing and 3D printing paper-based scaffolds for applications in biomedical field.