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Recent advances on bast fiber composites: Engineering innovations, applications and perspectives

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ABSTRACT

Plant fibers are a class of biomass resources one of most abundant materials on earth. The bast fiber, as one of the plant fibers with superior specific stiffness and strength, has received constant attention in the field of biocomposites for various industrial sectors. This study is to provide a comprehensive overview of bast fiber composites. The characteristic, chemical composition and performance of five types of most commonly available bast fibers (ramie, jute, kenaf, flax and hemp fibers), and their functionalization in biocomposites are analyzed. The engineering technologies and performance in uses, e.g. flame retardancy, adsorption, reinforcement, biodegradability green sustainability and recyclability of the bast fiber composites are assessed and compiled. The challenges and future development of bast fiber composites are also discussed. The review is expected to provide a platform database but insightful understanding for effective engineering design and broadened applications of bast fiber composites, and for further innovations of functionalized bast fiber composites.

1. Introduction

Renewable materials and innovative technologies that could cut down on the usage of petroleum are gaining popularity as a result of the growing interest in sustainability and environmental preservation [1–4]. Market demand has developed for more environmentally friendly materials with competitive qualities, comparable to petrochemical-based materials, at competitive pricing [5]. Natural fiber composites have grown in popularity over the last decade, with expanding applications in automotive, construction, biomedical, and even the military sector [6]. Natural fibers offer appealing qualities for the development of reinforcing materials, including low cost, low wear on equipment, outstanding specific strength and stiffness, and low density [7]. Furthermore, the exceptional eco-friendly, compatible and biodegradable features of natural fibers over petro-based fibers are compelling reasons to shift focus on using natural fibers for their composite developments, the supply chain of which is getting richer and more comprehensive (Fig. 1).

Animal fibers, mineral fibers and plant fibers are the three basic classifications of natural fibers [8]. Animal hair and silk strands are examples of animal fibers. Asbestos and basalt are the primary sources of mineral fibers. According to their origin, the plant fibers discussed in this article can be split into seven categories, namely bast fibers (ramie, jute, kenaf, flax, and hemp), stalk fibers (rice, wheat, barley), seeds fibers (cotton, kapok), wood (softwood, hardwood), fruit (luffa, oil palm, coir), grass (bamboo, bagasse) and leaf (sisal, palm, aloe vera) [9]. A clear categorization of the natural fibers is displayed in Fig. 1a. Although most of natural fibers are used in the fabrication of biocomposite materials as reinforcements, the usage of plant-based natural fibers is greater than that of animal- and mineral-based fibers, because animal-based fibers are more expensive and asbestos is suspected carcinogenic and associated with other health problems.

Among plant-based natural fibers, bast fibers, which mainly include ramie, jute, kenaf, flax, and hemp (Fig. 1b–c), are natural fibers with

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high mechanical properties that have grown in popularity in recent years [10,11]. Because of their biodegradability and availability in nature, bast fibers are interesting possibilities for the automotive sector, structural composites, pulping, and textile applications (Fig. 1d). Bast fibers also have some other advantages, including renewable supplies, ease of preparation, exceptional damping qualities and least abrasive damage to equipment [12]. Therefore, bast fibers are utilized as the reinforcement material in biocomposites to enhance their structural stability and mechanical properties [13]. Bast fiber reinforced composites may be appealing as an enticing option to synthetic fiber reinforced composites because of the increased demands for lightweight elements and reduced environmental impact [14]. The purpose of this article is to offer a comprehensive review of the properties of bast fiber reinforced composites employing various bast fibers including ramie, jute, kenaf, flax and hemp fibers. Furthermore, current developed novel engineering technologies as well as multiple applications of bast fiber reinforced composites were studied to provide a knowledge platform for engineering design and possible further innovations.

2. Structure and composition

Characteristic and structure of bast fibers are complex depending on the origin, location in the plant and processing (Fig. 2). Bast fibers and their composites have been employed in many fields including architecture, automotive, energy, biomedical and aerospace [9], depending on the availability and characteristics (Table 1). Ramie is the toughest bast fiber that yielded its fiber from the bark of the canes [16]. The global production of ramie fiber exceeds 52,000 tons in 2020 [17]. Ramie fiber has the characteristics of good toughness, low elongation, and resistance to insect damage and corrosion [18]. Jute fibers are commonly referred to as the "golden fiber" [19]. In terms of production, jute is the second-most significant natural fiber after cotton. Jute fibers are being produced annually in the world in 3.2 million tonnes [20]. The largest jute producing countries are Bangladesh and India [21]. Kenaf has become a significant plant grown in third-world nations [22]. Approximately 970,000 tons of kenaf fiber are produced globally [23]. Due to its excellent properties such as low density and mechanical strength, it has great potential as an alternative reinforcement material. Flax fiber is one of the most preferred natural cellulose fibers, known for its comfort, strength and durability [24]. The worldwide production of

Fig. 1. Supply chain of natural fibers and biocomposites: (a) category of natural fibers [15], digital photos of (b) bast plants and (c) bast fibers, and (d) representative biocomposites in automotives, smart textiles, biodegradable food tools, and constructions.

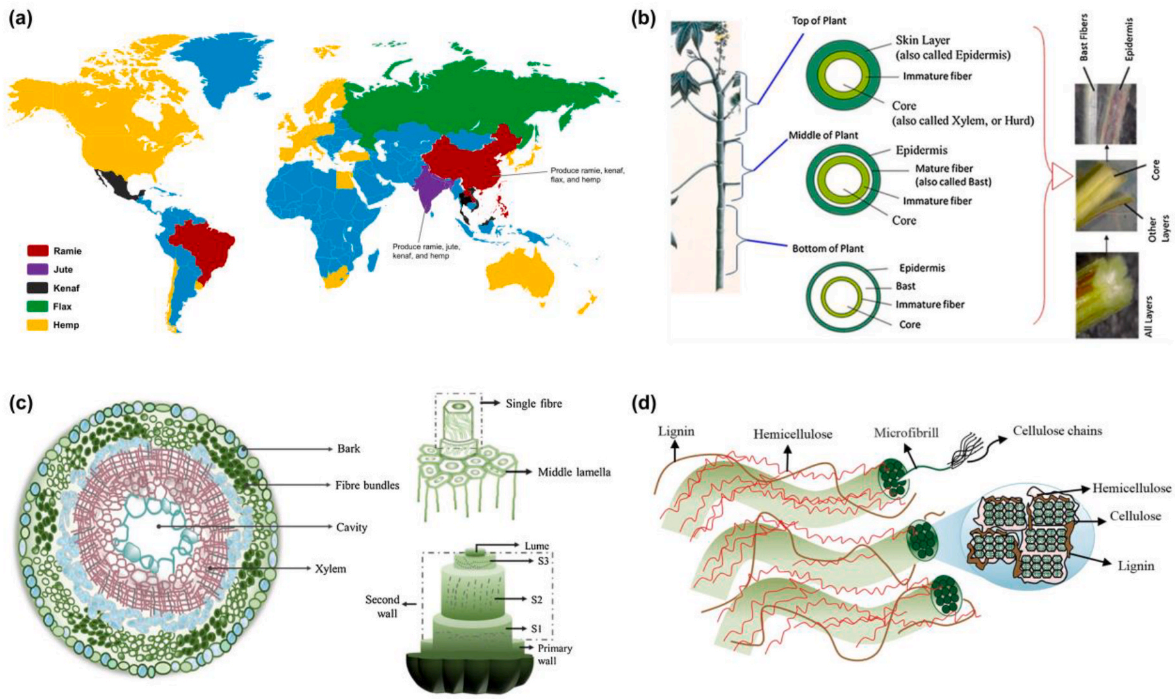

Fig. 2. Characteristic of bast fibers: (a) global distribution of countries producing typical bast fibers [15,30,34], (b) stem and fiber [28], (c) cross-section view [27] and (d) major chemical components of natural fibers [9].

Table 1
Dimensions, mechanical properties and major countries of production of typical bast fibers [9,15,29–33].

Fibers	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Major countries
Ramie	18–80	40–250	400–938	44–128	2.0–3.8	China, Brazil
Jute	5–25	0.8–6	400–800	10–30	1.5–1.8	Bangladesh, India
Kenaf	12–36	1.4–11	284–800	21–60	2.7–6.9	China, India
Flax	5–38	10–65	800–1500	60–80	1.2–1.6	China, France
Hemp	10–51	5–55	550–900	58–70	1.4–3.5	Chile, China

flax fiber is around 311,000 t that is reported in the year 2014 [25]. Hemp originated in Central Asia and is now widely grown all over the world. Industrial hemp cultivation in Europe reached a record 33,000 ha in 2016 [26]. Hemp has sparked widespread interest because to its biodegradability, inexpensive cost, and quick growth in both mild and hard climatic conditions [27]. Due to the low density, the tensile strength and Young's modulus of bast fibers are quite comparable to synthetic fibers, making them attractive enough for advanced composite applications. At present, bast fibers are produced for commercial or research purposes in many countries and regions including Europe, China, Brazil, India, USA and Canada (Fig. 2a). When the stem of a bast plant is viewed under a microscope, three layers may be identified: the extremely thin epidermal layer, the layer of fiber encircled by the phloem and the xylem or core layer (Fig. 2b) [28]. A whole bast fiber plant, seen from a cross-section, consists of bark (also called skin layer or epidermis), fiber bundles, and xylem (Fig. 2c).

The chemical composition of bast fibers varies among different species of bast plants (Table 2). Obviously, cellulose, hemicellulose and lignin are the main components of typical bast fibers, with pectin and wax making up a very small portion. Cellulose makes up the majority of the chemical composition of bast fibers (Fig. 2d). It is worth mentioning that cellulose content positively affects the mechanical performance and utilization potential of bast fibers and their composites [27].

Table 2
Chemical components of different bast fibers [27].

Fibers	Chemical composition (%)				
	Cellulose	Hemicellulose	Lignin	Pectin	Wax
Ramie	68.6–91	5–16.7	0.6–0.7	1.9–2	1–2
Jute	51–84	12–20	5–13	0.2	1
Kenaf	44–57	21	15–19	0.6	0.5
Flax	60–81	14–19	2–3	1.8–2.3	1–2
Hemp	55–77	14–22.4	3.7–13	0.9	2

3. Advances in ramie fiber composites

Ramie bast fiber is a relatively strong and tough biomass fiber with excellent physical and mechanical characteristics, such as large length and low shrinkage, and promises to be an alternative to synthetic fibers in the application of clothing fabrics, industrial packaging, safety ropes, armors, car outfits and fiber reinforced composites [35–38]. Specifically, ramie fiber reinforced polymer composite is an emerging sustainable material and has attracted considerable attention in recent years [39,40]. On account of the advantages of biodegradability, low density and low-cost benefits, ramie fiber composites have been widely used in flame-retardant [41], fabric [42], biodegradable/recyclable [43] reinforced biocomposites [44].

3.1. Ramie fiber based flame-retardant composites

Even though ramie fiber composites are preferred for environmentally friendly and sustainable products, the low flame retardancy of ramie fibers limits their application in composites. Therefore, significant studies have been conducted to solve the flammability issues of ramie fiber composites and practical strategies have been exploited by employing various types of flame retardants (Fig. 3). Zinc chloride and borate, ammonium phosphate and borate, sodium borate, ammonium sulfate and chloride, and others are among the most widely used flame retardants [29].

Flame-retardant ramie fabric/bio-based epoxy resin composites have recently been designed by coating cationic polyethyleneimine (PEI) and anionic ammonium polyphosphate (APP) on the surface of ramie fabrics (RF) through layer-by-layer assembly [45], followed by compression molding technology (Fig. 3a). The modified RF (MF) reinforced epoxy resin (EP) composite exhibited a significant decrease of peak in heat release rate (285 kW/m^2) compared to the original RF/EP composite (608 kW/m^2). The improvement of flame-retardant properties followed the mechanism of the catalytic dehydration and charring effect by phosphorus-containing acids from the degradation of APP. Besides, compared with neat EP, the flexural strength of EP/MF composite upgraded by 29 %, demonstrating significant reinforcement of ramie fabric. Another flame retardant RF based full biocomposite, RF reinforced PLA composite, has also been developed through a melt-blending method [46] by mixing the flame retardants of aluminum diethylphosphinate (AlPi), melamine cyanurate (MCA), SiO_2 or their combinations respectively; the PLA and RF were pre-heated at 190 °C and molded in a twin-screw injection machine at 215 °C (Fig. 3b). It must be noted that an integration of the flame retardants resulted in a decrease in the tensile strength but had no impact on the tensile modulus RF composites. Furthermore, because of the synergism between AlPi, MCA and SiO_2, the high-grade char layers were formed quickly and the flame retardancy of RF/PLA composites was promoted (Fig. 3c).

A straightforward dip-pad-bake strategy was employed to develop a flame-retardant ramie fabrics by coating ammonium polyphosphate (APP) on ramie fabrics (RF) [47]. The presence of APP enhanced the flame retardancy of the composites while also exhibiting a remarkable ability to control smoke. During the thermal degradation of ramie fabrics/APP composite, the amount of flammable gases produced could be reduced, which in turn reduced their concentration and prevented combustion (Fig. 3d). At the same time, the fabrics may be dehydrated and carbonized by APP, creating thick char layers that prevented heat transfer. Jiang et al. [48] reported a flame-retardant ramie fabrics reinforced epoxy resin composites fabricated through hand lay-up technology after coating ammonium polyphosphate (APP) on the surface of ramie fabrics. The obtained EP/RF-APPs exhibited the needed good flame retardancy and acceptable fire safety when compared to EP/RF (Fig. 3e). Additionally, the EP/RF-APP20 achieved UL-94 V-0 rating standard with 33.8 % LOI when APP reached 20 wt% weight gain on RF. Moreover, although the presence of APP could significantly improve the flame retardancy of the composites, the amount of APP could affect the consistency within the matrix, descending to some extent overall mechanical performance.

As discussed above, flame retardants can be uniformly coated on the surface of ramie fiber or fabric composites, which limits heat transfer due to the formation of thick char layers and reduces the concentration of flammable gases during the thermal degradation. These advantages can make flame-retardant ramie fiber or fabric composites materials widely used in construction, aircraft and automobiles. Nevertheless, due to a certain degree of decline in mechanical properties and compatibility, some industrial uses of composite materials are restricted. Therefore, research on flame-retardant ramie fiber or fabric composites materials remains very active.

3.2. Ramie fiber based fabric composites

Another major development is novel ramie fiber fabric composites [42,49–51]. Due to the exceptional reliability, structural stability and designability, ramie woven fabrics become one of the most popular reinforcement materials and are particularly useful for producing homogeneous laminated woven fabric reinforced composites. Tensile

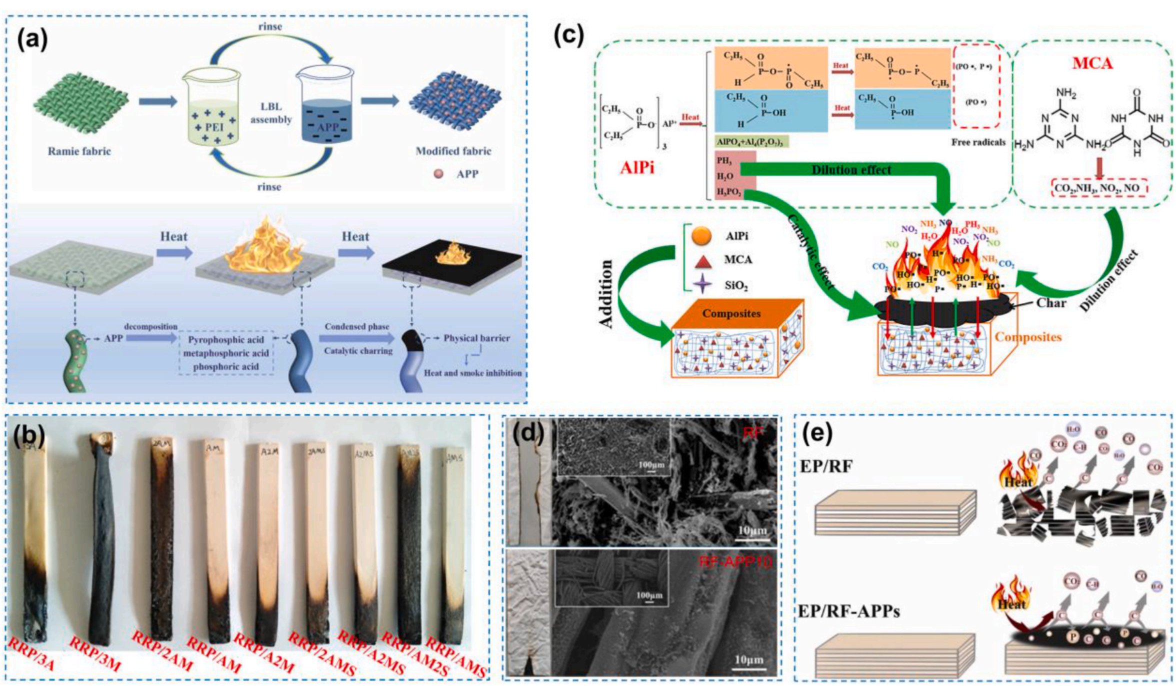

Fig. 3. Flame retardant formulation and mechanisms of ramie fiber/fabric full biocomposites: (a) production and flame-retardant characterization of EP/MF [45], (b) ramie fiber/PLA composites after burning [46], (c) flame-retardant mechanism [46], (d) morphology of tested of samples [47] and (e) graphical illustration of flame-retardant mechanism of EP/RF-APPs [48].

properties are considered to be the basic index of green ramie fabric composites for a variety of engineering applications, including the automotive industry, spacecraft parts, construction, sports equipment, bulletproof vests, etc. Tensile properties could be advanced through manufacturing designs, e.g. yarn and fabric designs (Fig. 4a), the tensile loads of ramie woven fabric reinforced composite, whether single or multi-layered, was considered as the accumulation of tensile loads in either warp or weft reinforced composites [38], although single-layer ramie woven fabric reinforced composites produced more accurate prediction of tensile strength than multi-layer ramie woven ones. A similar work presented by Zuo et al. [50] using a ramie fabric/unsaturated polyester showed that the composite prepared from a ramie fabric with a density of 135 g/cm^2 had the strongest resin permeability (Fig. 4b), tensile strength of 61.44 MPa, tensile modulus of 3.34 GPa, flexural strength of 76.90 MP, flexural modulus of 3.16 GPa, and storage modulus of 5151.35 MPa because of high apparent porosity of the ramie fabric and high efficiency load-bearing structure of composites. Cheng et al. [51] developed a durable electromagnetic interference (EMI) shielding ramie fabric composite (Fig. 4c). Through depositing technology with ammonium polyphosphate (APP)/polyethyleneimine (PEI) layer, MXene sheets and polycaprolactone (PCL) layer, the fabricated ramie fabric composite also had superior flame retardant and self-healing performance. Ramie fabric composites coated with more MXene sheets underwent a transition from insulating to conducting, gradually enhancing their EMI shielding ability. These fabric composites had a high electrical conductivity of 900.56 S/m and a superb SE value of 35 dB at a 1.2 mg/cm^2 content in the X-band. This multifunctional ramie fabric composite has broad application prospects in fields such as wearable smart cloth and EMI shielding. Additionally, ramie fiber reinforced epoxy resin composites have been fabricated by combining ramie fiber fabric (RFF) with epoxy resin (EP) and silicon polymer (PSOL) [52], as demonstrated in (Fig. 4d). After PSOL modification, surface adhesion between EP and RFF was significantly enhanced, and the mechanical properties (such as flexural strength and tensile strength) of the PSOL/RFF/EP composite laminates were also improved.

Apart from the above-mentioned ramie fiber/epoxy resin composites which have been extensively investigated, more biodegradable ramie fibre composite has recently emerged, e.g. ramie yarn/polylactic acid (PLA) woven-like biocomposite, which showed potential for wide applications with outstanding mechanical properties [53]. Through in-situ impregnated 3D printing technology on the basis of an interweaved and printing method, ramie fibers can effectively enhance the permeability of the PLA matrix (Fig. 4e). This biocomposite holds great promise in biodegradable and renewable reinforced material. However, there are still some challenges in the development of ramie woven fabric reinforced composites. For example, it is difficult to recover ramie woven fabric and epoxy resin or PLA separately after being discarded or damaged due to their close integration. Moreover, under the combined effect of humidity and heat, aging occurs in ramie woven fabric reinforced composites, which seriously reduces the service life. Hence, how to improve the aging-resistance of such biocomposite materials remain challenged before viable industrialization and efficient utilization.

3.3. Ramie fiber based biodegradable/recyclable composite films

The biodegradability of RF based composites has become of importance and some attempts have been made. For instance, the chitosan/ramie fiber/lignin composite films have been developed to replace non-biodegradable food packaging materials (Fig. 5a) [54]. Significant improvements in mechanical properties, water resistance and antioxidant performances were achieved after adding different proportions of ramie fiber and lignin to the chitosan matrix. In comparison to the CSR0L0 film, the addition of 20 % wt ramie fiber could raise the tensile strength from 44.6 MPa to 57.8 MPa, and most promisingly after adding 20 % wt lignin, the antioxidant activity could be boosted by 288 % and water resistance could be increased by 41.2 %. The pH of the chicken breast packaged in chitosan/ramie fiber/lignin composite film remained in the acceptable range after 7 days of storage, and there were significantly

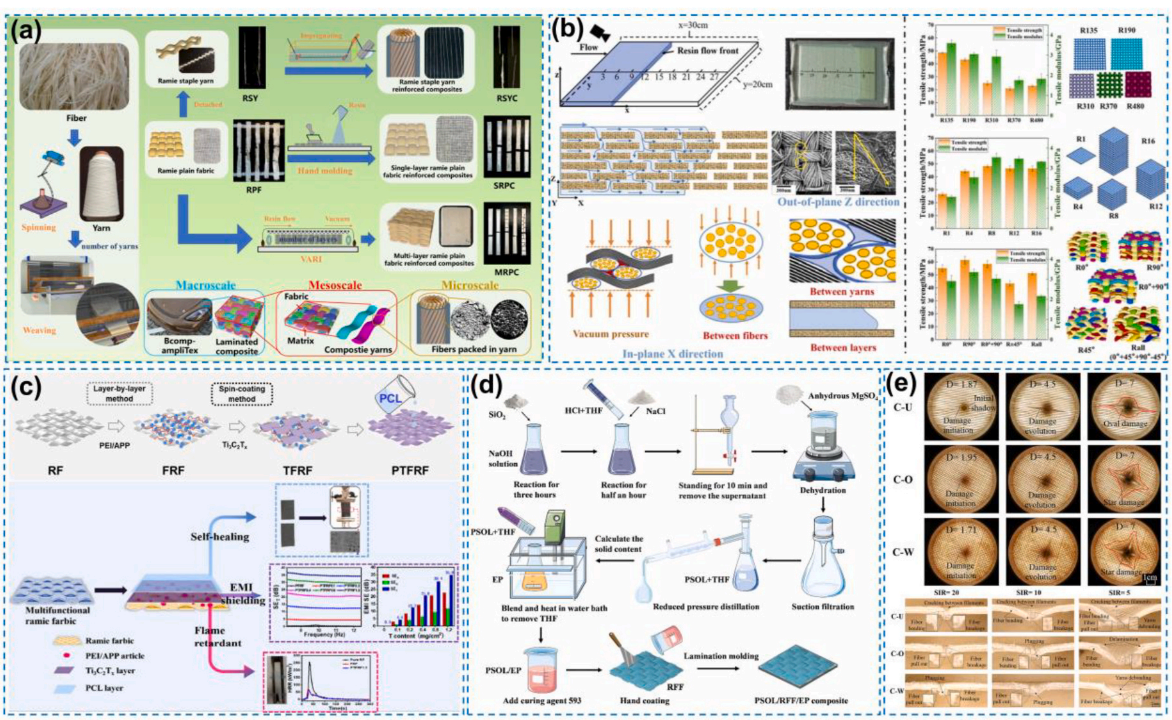

Fig. 4. Innovations of RF composites for various applications: (a) fabrication of multi-scale structural ramie woven fabric/resin composites [49], (b) ramie fabric/unsaturated polyester composites [50], (c) multifunctional ramie fabrics and its electromagnetic interference (EMI) shielding [51], (d) preparation of PSOL/RFF/EP composite laminate [52] and (e) damage evolution in ramie fiber reinforced biocomposites and cross-section of biocomposites after the penetration tests [53].

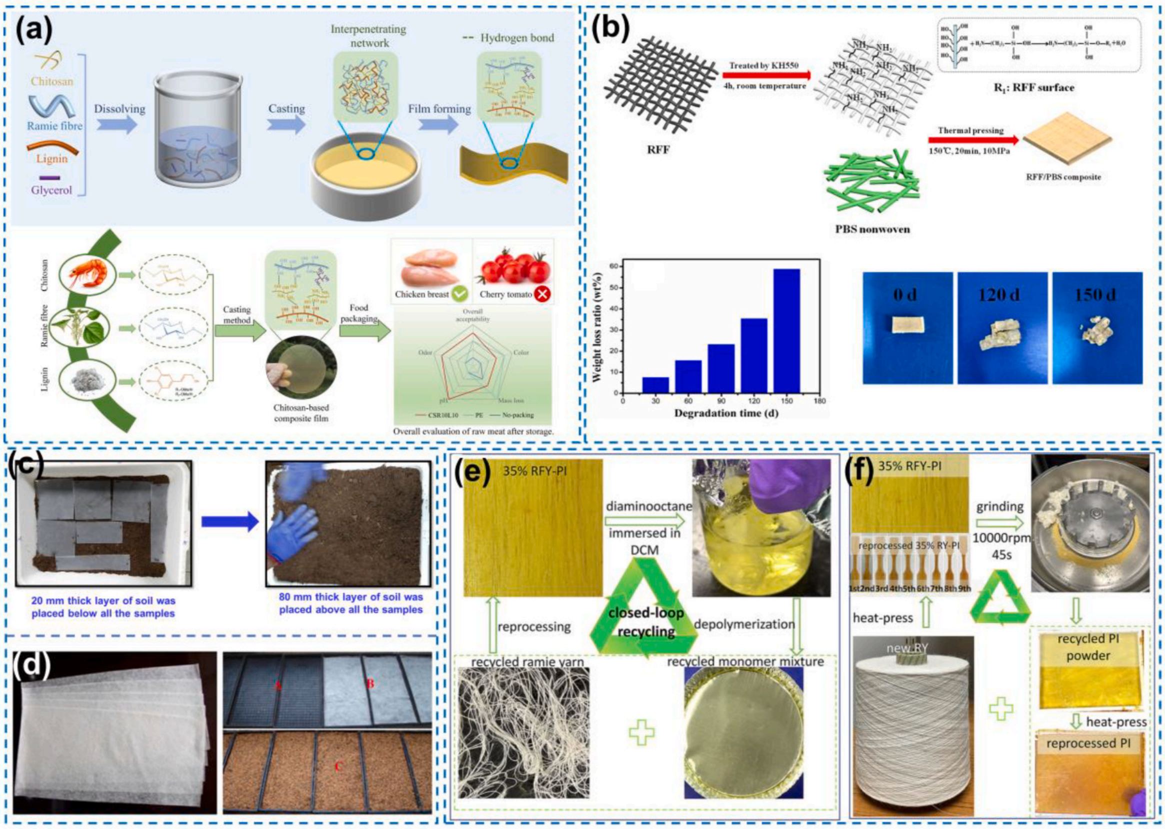

Fig. 5. Development of biodegradable ramie fiber biocomposites: (a) schematic illustration of biofilm preparation [54], (b) preparation of RFF/PBS biocomposite [55], (c) degradation study in soil [56], (d) Ramie fiber/starch nonwoven film in degradable experiment [57], (e) closed-loop recycling of RY-PI through a chemical strategy [58] and (f) physical recycling of RY-PI [58].

fewer developed microorganisms than when the chicken breast was wrapped in PE film. The ramie fiber composites seem to hold great potential in biodegradable food packaging. Han et al. [55] reported an amino functionalized ramie fiber fabric (RFF)/poly(butylene succinate) (PBS) biocomposite prepared by an easy thermal-compressive strategy (Fig. 5b). In contrast to prior approaches, PBS nonwoven was used as a raw material for the matrix and three-dimensional network structure achieved to successfully anchor RFF, producing superior penetration and considerable improvement in mechanical performance. The biodegradability of RFF/PBS biocomposites makes them an ideal substitute for traditional nondegradable composites. Ramie fiber reinforced PLA composites can be degraded in nature, but the rate of degradation is not satisfactory. Therefore, additives (such as polyethylene glycol and triethyl citrate) were doped into ramie fiber reinforced PLA composites to accelerate the degradation behavior [56]. After ramie fabric was modified with diammonium orthophosphate, ramie-PLA composites could be degraded thoroughly after two months of soil burial (Fig. 5c). The addition of additives in ramie fiber reinforced PLA composites helps to improve the degradation rate and make the material environmentally friendly, thus providing a practical alternative for other materials. Plastic agricultural nonwoven films have long been utilized as covering materials, unfortunately their poor biodegradability makes them prone to causing a variety of environmental issues. A nonwoven film composite made of ramie fiber and starch has recently been created and used as bedding material under cultivated soil [57]. The fabricated ramie fiber/starch nonwoven film exhibited a loose, porous structure with a primary pore size of 250–300 μm and good biodegradability (65.6 % after 72 days) (Fig. 5d).

A possible method to reduce plastic waste and lessen its negative effects is to manufacture natural fiber-reinforced plastic composites (NFRPCs) using cellulosic fibers. However, NFRPCs cannot replace nondegradable plastics on a large scale because of their poor tensile strength and difficulty in recycling. Li et al. [58] fabricated an efficient ramie yarn-reinforced polyimine vitrimer composites (RY-PI) that can be chemically and physically recycled. Through hydrogen bonding, the polyimine matrix and ramie yarn created a strong bonding contact. This RY-PI was also lightweight, strong, self-healing, moldable, resistant to organic solvents, and moisture barrier resistant. The RY-PI could be closed-loop recycled using a chemical method with no performance loss (Fig. 5e). Besides, a highly efficient (11 min for each recycling), low-cost, and environmentally benign (no chemicals added) RY-PI physical recycling system was presented (Fig. 5f). It can be seen that RY-PI could be an environmentally acceptable substitute for many common plastic products to facilitate the achievement of zero plastic waste with its great performance and high recyclability. As suggested by the abovementioned discussion, ramie fiber/biodegradable polymer composite is a new type of advanced composite material with the advantages of full-component green, low cost, lightweight and high strength, which is of great significance for the protection of environment, effective use of biomass resources, and promotion of a green production and life. However, further exploration of the interaction mechanisms between ramie fibers and biodegradable polymers is needed to provide theoretical support for the structural design and preparation of composite materials.

3.4. Formulation of ramie fiber as reinforcements

The research on ramie fiber as a sustainable reinforcement in hybrid composite system has seen significant growth in recent decades (Fig. 6). One aspect of these developments is to improve the bonding interface of the composite with nanotechnologies, e.g. using graphene oxide (GO) with varying particle sizes to create ramie fiber (RF) reinforced

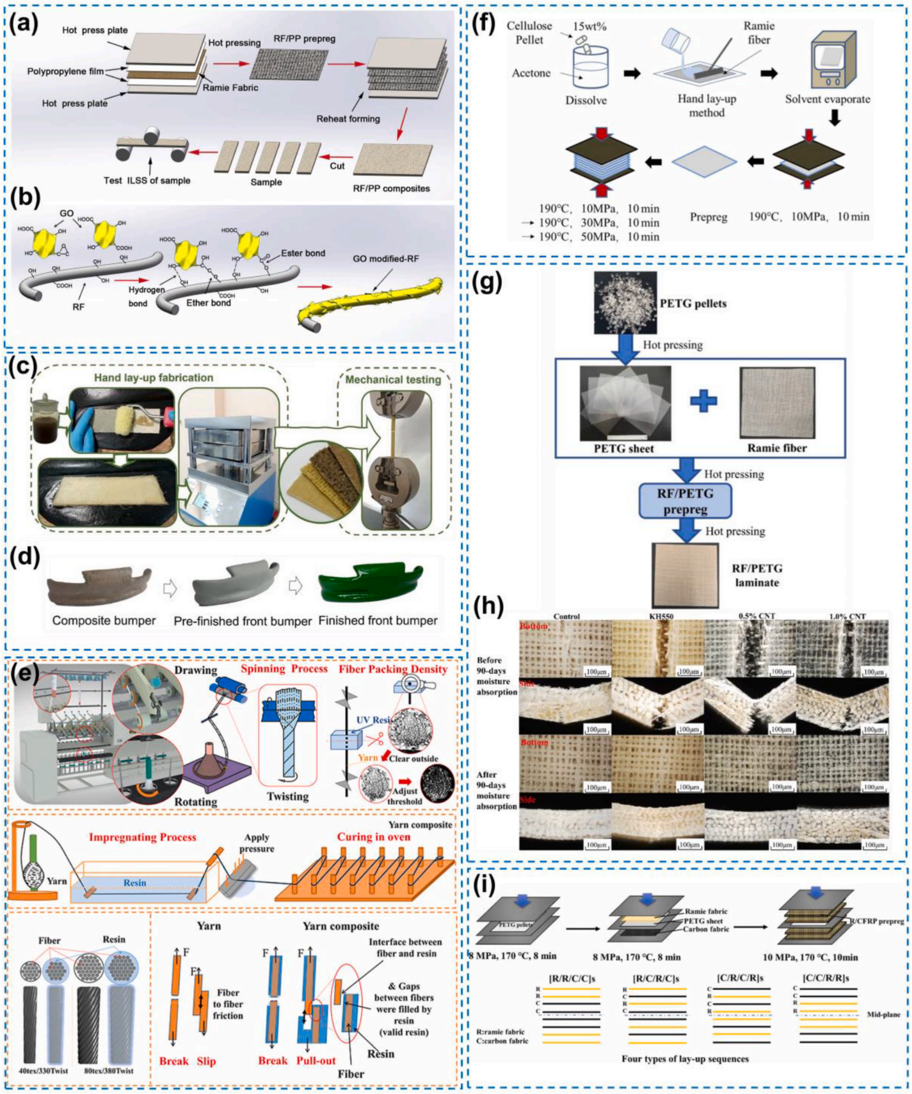

Fig. 6. Ramie fiber as a reinforcement for structural composites: (a–b) manufacture of RF/PP composites and bonding of GO-RFs [59], (c) ramie fiber reinforced FDCA-derived PEUA composites and (d) their production of front bumper [63], (e) preparation of RSYs and RSYCs [60], (f) production of ramie fiber/cellulose acetate resin composite [61], (g) fabrication of RF/PETG laminate composites and (h) bending fracture before/after 90-days hygrothermal aging [62], and (i) manufacture of R/C hybrid composites [64].

polypropylene (PP) composites in order to increase interlaminar shear strength (Fig. 6a–b) [59]. The interfacial connection between RFs and PP matrix was thought to be improved by the wrinkle shape of GO surfaces, which would then improve stress transfer from the PP matrix to the RFs. Another interesting development has been to formulate structural full biocomposites, e.g. ramie fiber, as reinforcement and 2,5-furandicarboxylic acid (FDCA) as a green platform chemical to address global sustainability challenges [49]. The ramie fiber reinforced FDCA-derived PEUA composites was reported to demonstrate high tensile (~30 MPa) and flexural (~60 MPa) strength (Fig. 6c). This outstanding mechanical performance provides a great potential for lightweight vehicle applications (Fig. 6d), promoting the circular economy and expanding the sustainable polymer industry.

Utilizing staple spinning to provide continuity on short fibers allows for the circumvention of plant fiber length restrictions. In Zuo et al.'s work [60], ramie fiber staple yarn (RSY) reinforced unsaturated polyester composites (RSYCs) were prepared using ramie fiber as reinforcement and unsaturated polyester resin (UPR) as the matrix (Fig. 6e). The failure mode of RSYs to RSYCs shifted from slipping to ripping out after UPR resin impregnation. RSYCs possessed larger breaking forces and tenacities than RSYs, although their breaking elongations had decreased. Sun et al. [61] studied the tensile properties of green composites based on cellulose acetate resin with ramie fiber nonwoven, fabric, yarn and sliver (Fig. 6f). Among the four material structures used in the unidirectional composites, the ramie fiber sliver performed better as a reinforcing material. By comparing the tensile strength of the single fibers heated at different temperatures, it was discovered that the hot-pressing temperature should be kept below 200 °C while creating ramie fiber reinforced green composite materials to prevent the loss of mechanical characteristic. As the percentage of ramie fiber volume rose, the tensile strength and tensile modulus also increased. In Li et al. work [62], the ramie fiber (RF) reinforced polyethylene terephthalate glycol (PETG) composites modified with silane coupling agent and carbon nanotubes (CNTs) were prepared by hot pressing method and their mechanical properties were investigated (Fig. 6g–h). In comparison to untreated composites, the bending strengths of RF/PETG composites modified with silane coupling agent, 0.5 wt% CNTs and 1.0 wt% CNTs increased by 8.5 %, 16.9 %, and 20.5 %, respectively. With an increase in aging time, the bending strength and modulus of the RF/PETG composites initially declined quickly and then slowly. An investigation of hybrid ramie and carbon fiber (R/C) reinforced polyethylene terephthalate glycol composites have also been carried out (Fig. 6i), showing a significant impact of lay-up procedures on the flexural strength and modulus of R/C hybrid composites. When carbon fibers were presented in the outer layer of the composite, the flexural strength and modulus of laminates were higher than that in inner layer. The R/C hybrid composites could be further optimized, especially for technical applications in marine and automotive fields. It is evident that the ramie fiber has a great potential as reinforcing components for green composites with superior mechanical properties. Nevertheless, some challenges, e.g. the poor interfacial compatibility and uneven dispersion, remain. If the size of ramie fibers is reduced to the nanometer scale and ramie nanofibers are prepared, the dispersion of ramie fibers in polymers and the homogeneity of composites may be improved, and the interfacial compatibility of ramie fiber and composites may be enhanced.

4. Advances in jute fiber composites

Jute fibers have been an attractive option as bio-based ingredient for the preparation of composites because of inexpensive price, light in weight, long fiber length as well as good mechanical performance [65–67]. Increasing attentions have been paid to the adsorption, flame-retardant, reinforcement and automobile application innovations of jute fiber replacing ecologically damaging synthetic fibers [68–73], and to the development of various whole biocomposites, e.g. jute/rubber flexible bio-composite [74], jute-soy protein composites [75], jute/PLA composite [76].

4.1. Jute fiber composite as absorbents

One of the most interesting advances is in absorbent jute fiber composites (Fig. 6). An immediate attention is paid to create adsorbents that can efficiently extract uranium from saltwater while also being strong and environmentally safe, as oceanic uranium resources are abundant and a perfect replacement for the rapidly running out uranium mines on land. Polyamidoxime (PAO)-grafted cellulose-based jute fabric (Jute-TMC-PAO) composites were prepared using a simple etching-grafting-hydrolytic method (Fig. 7a) [77]. A uniform PAO layer was coated onto the alkali-treated jute fabric surface through covalent bonding with trimesoyl chloride (TMC) as a bridging agent, and then carboxyl group was generated by hydrolysis. The obtained Jute-TMC-PAO composites were extremely strong with a tensile strength of 376 MPa and presented as a good engineering alternative for extracting uranium from saltwater, giving an effective uranium adsorption rate of 0.233 mg g^{-1} day^{-1} in simulated natural seawater.

Fig. 7. Advances on jute fiber composite absorbents: (a) grafting model and reaction route of Jute–TMC–PAO and uranium adsorption model in uranium-spiked water/seawater [77], (b) prepared non-woven jute fibers-derived sorbents [22], preparation of (c) superhydrophobic jute fiber sponge [78] and (d) jute fiber-derived sorbent and its efficient oil spill clean-up [79].

Another advance development is on the jute fiber composite for oil-water absorption or filtration to meet the need for an effective, environmentally friendly, and commercially viable solution to the increased oil exploitation and frequent oil spills harming ecosystems. A non-woven sorbent based on recycled jute postindustrial textile waste has been attempted to create an effective, reusable, biodegradable, and affordable sorbent for oil clean-up (Fig. 7b) [22]. Although the jute sorbent esterification with stearic fatty acid increased its hydrophobicity and decreased water uptake, its effect on oil sorption behavior can be disregarded. Even after five squeeze cycles, the jute fibers-derived sorbents primarily kept 50 % of their initial oil sorption capabilities. To create cost-effective responses to oil spills, further advance has been attempted by introducing sol-gel and freeze-drying techniques to create cellulose sponge from scrap jute bags that contained 60–65 % cellulose (Fig. 7c) [78]. The oil-water separation efficiency of dip coated jute cellulose sponge for diesel and motor oil achieved 98.5 % and 97.2 %, respectively. It is apparent that the waste jute bags have significant promise as a source of low-cost superhydrophobic materials for the cleanup of crude oil spills. This technique could also be applied to other types of waste biomass and crop leftovers. Although loose assemblies of jute fibers may be used to clean up oil spills, it would be difficult to remove them from the spill once they were finished. In order to address this problem, Kovačević et al. [79] developed a renewable sorbent derived from recycled jute fibers from carpet factories (Fig. 7d). With regard to oil retention after 3 h, the carbonized jute fibers-derived sorbent demonstrated greater buoyancy even after 24 h and only a 12–20 % loss in oil sorption capacity after five iterations of sorption/desorption, and the oiled non-carbonized sorbent is a viable option for cleaning up oil spills because of its capacity to efficiently decompose in a model compost (up to 45 % weight loss after 10 weeks). In summary, the use of jute-based adsorbents shows considerable promise, though the investigations carried out in these labs made use of tiny, batch-sized adsorbents. Industrialized technologies are yet to be further developed and the use of jute-based composite adsorbents shall increase when effective manufacturing procedures continue to be developed.

4.2. Jute fiber based biodegradable composites

In common with other natural fiber composites, significant innovations on true biodegradable jute fiber composites have arisen recently (Fig. 8). The combination of polylactic acid (PLA) and jute fibers seems most intriguing to provide a fully biodegradable property and exceptional mechanical characteristics (Fig. 8a) [80]; the jute/PLA composites could be degraded in an enzymatic environment with three distinguished stages in the presence of protease K, cellulase, ligninase, and pectinase in an enzyme solution. The majority of the primary degradation firstly occurred in the amorphous PLA molecules, which degrade quickly; the second stage enzymatic degradation primarily affected the fiber-matrix interfaces and the PLA crystalline region; and finally jute fiber started to degrade and PLA started to collapse after the crystalline region was broken down by enzymes. Biodegradable jute/-PLA composite materials have also been created utilizing a PLA film-stacking technique [81], employing PLA as the matrix and jute fiber as reinforcement (Fig. 8b). This biodegradable composite material offered a wide range of possible applications due to its benefits of low cost, simple manufacture, light weight, and strong mechanical qualities. Marczak et al. [82] introduced a needle-punched nonwovens made from wool and linen or reinforced by jute mesh. This biocomposites could be biodegraded after the first vegetation season (Fig. 8c). Biodegradable geotextiles installed in soil could provide instantaneous protection, and their gradual decomposition can cultivate plant vegetation. Biodegradable jute/PLA composite could be created by combining jute fibres and PLA through a compression molding method (Fig. 8d) [83], allowing the addition of more jute layers, which could improve the tensile and flexural strength of the composites. This jute/PLA composites exhibited excellent characteristic of low density, affordable price, biodegradable and outstanding mechanical capabilities, and have showed a promising future in building construction, furniture, retrofitting and automobile interiors. It can be concluded that there have been a few applications and research on fully biodegradable jute matrix composites due to the immaturity of the preparation process of fully biodegradable jute matrix composites. Jute fiber-based composite is becoming a research hotspot in the field of agricultural environment. Maintaining good mechanical strength may sacrifice lightweight of the biodegradable composites,

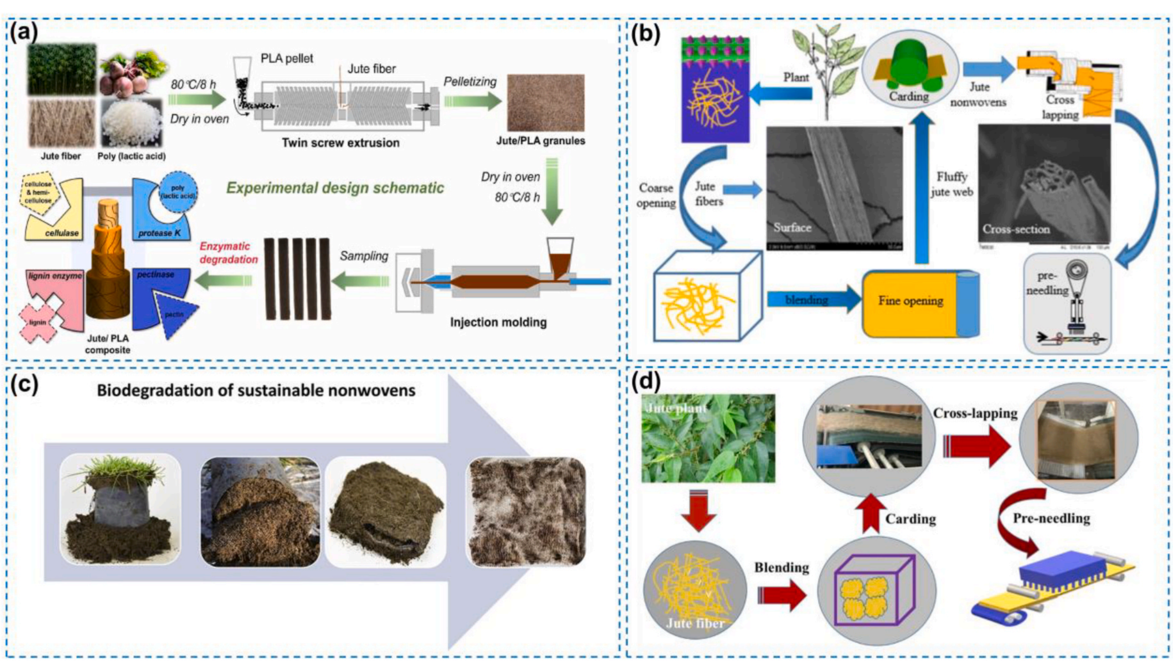

Fig. 8. Advances on biodegradable jute fiber composites: experimental design of Jute/PLA composites (a) [80] and jute/PLA film staked composites (b) [81], (c) biodegradation of jute fiber composites [82] and (d) fabrication of jute nonwovens [83].

hence, research in this area must address the balance between weight and mechanical strength.

4.3. Jute fiber composite as reinforcements

Jute fiber has demonstrated prospectives for replacing aramid glass fiber and other synthetic fibers as composite materials reinforcement (Fig. 9). An advanced jute fiber reinforced vinyl ester based biocomposite has been developed after jute fiber underwent in-situ treatment in a solution of sodium hydroxide and magnesium nitrate while being exposed to microwave irradiations (Fig. 9a) [84]. After adding Mg^{+2} doped jute fibers that had been treated with 0.25 M solution, the tensile and flexural properties significantly increased, and flame retardancy of the biocomposite slightly enhanced. The composite research community still has a significant difficulty in selecting the yarn liner density, optimizing the fabric structure, and further modifying the composites to get the optimum mechanical performance. Several woven jute fabric derivatives with equal linear densities of yarn were created to examine their reinforcing ability in polyester-resin-based composites (Fig. 9b) [85]. Comparing the 3/1 twill structured composites to the plain and other twill derivative structure composites, it was discovered that the 3/1 twill structured composites had better tensile, flexural and impact strength. After using γ-irradiation, further increases in tensile and bending properties of ~24 % and ~30 % could be observed, possibly because the crosslinking between the polyester matrix and jute fibers has been improved. Industrial tasar silk waste (TSW) and jute fiber were used as reinforcement in epoxy to create a hybrid composite for physio-mechanical characteristics and sliding wear characterization [86]. Compression molding was used for the preparation of TSW/jute fiber/epoxy composite at a pressure of 2 MPa to minimize the void formation (Fig. 9c). The tensile, flexural, impact strength and hardness of TSW/jute fiber/epoxy composites were significantly improved with a TSW addition of 12 wt%. The bio-based vanillin epoxy (VE) resin was prepared and added in alkali-treated jute fiber (TJF) mats through a straightforward solvent-epoxy process using the vacuum-assisted resin transfer molding method (Fig. 9d) to improve the adhesion strength and volume fraction of the green and efficient composites [87]. The prepared composite had outstanding flexural strength of 138.72 ± 3.81 Mpa, flexural modulus of 8.01 ± 0.11 Gp and Tg of 165 °C. Alkandary et al. [88] developed a hybrid green composite prepared by rice straw (RS) and jute fabric (JFa) and a soy protein isolate-based resin (SPR) (Fig. 9e). The RS/JFa reinforcement worked well in reinforcing the green SPR by enhancing its Young's modulus and tensile strength by up to 175 % and 47 %, respectively. A range of jute fiber-reinforced polypropylene composites were also created using the mixing-hot-pressing technique using polypropylene and jute fiber as the raw components (Fig. 9f) [89]. The highest tensile strength and flexural strength were attained at a fiber content of 35 %, with the mechanical characteristics increasing initially and then decreasing as fiber content rose. Moreover, by appropriately modifying processing parameters, the jute fiber-reinforced polypropylene composites exhibited acceptable sound absorption capability without sacrificing mechanical property, proving that the composite materials have prospective future for acoustic purposes. At present, research on jute fiber reinforced resin matrix composites mainly focuses on molding process and interface modification. While these research directions are still of great significance to produce high-performance jute fiber composites, further exploration is needed. Optimizing the processing parameters to facilitate industrial production and developing matrix modification reagents to enhance and toughen composites are especially crucial.

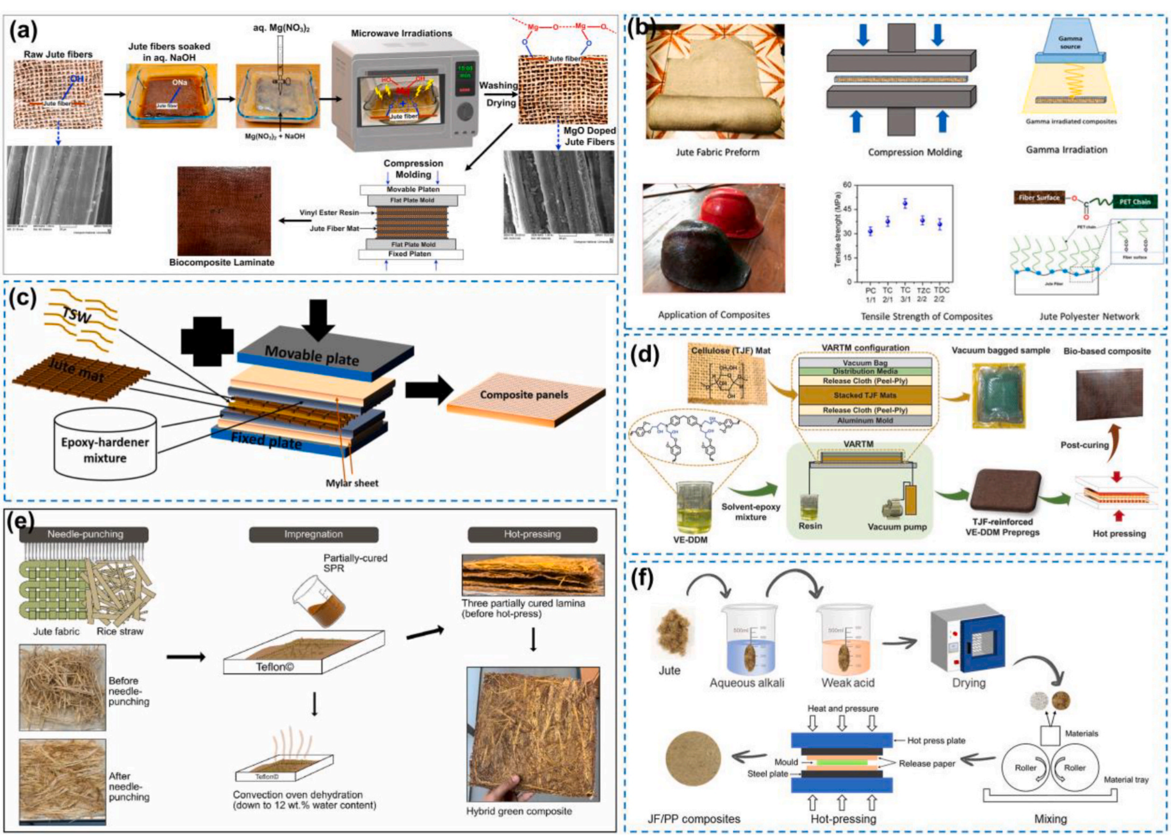

Fig. 9. Jute fiber as natural reinforcement replacing synthetic reinforcement: production of jute biocomposites laminate (a) [84], jute fiber reinforced polyester composites and its application (b) [85], tasar silk waste/jute fiber hybrid composite (c) [86], (d) VE-DDM/TJF composites (d) [87], hybrid composite fabrication process (e) [88] and jute fiber-reinforced polypropylene composites (f) [89].

4.4. Jute fiber based other functional composites

The two additional aspects of jute fiber composite innovations are energy materials and recycling (Fig. 10). A lightweight effective electromagnetic interference (EMI) shielding material has been reported [90] by employing jute fibers as precursors via a straightforward high-temperature carbonization procedure and dip-and-dry technique, (Ti_3C_2Tx)/jute composite (MXene/CJ) (Fig. 10a). The MXene/CJ composite showed exceptional electrical conductivity and EMI shielding capabilities after MXene was added to CJ. More importantly, the MXene/CJ-3 composite demonstrated good strain sensing capability and had exceptional sensitivity and reaction time at low pressure, indication the potential of MXene/CJ composite as a multifunctional material for wearable electronics and EMI shielding. A jute-reinforced polypropylene (JP) biocomposite has also been made and tested for use as a building heat insulation material (Fig. 10b) [81]. Since jute fiber and polypropylene have a strong interfacial adhesion, the produced JP composites have significantly higher tensile and flexural strength than the commercial counterparts and demonstrated a decreased thermal conductivity (0.165 W/m K). Thus, it is anticipated that using such heat-insulating engineered biocomposites in the design of green buildings will reduce the rising global CO_2 emissions caused by the energy consumption of buildings and encourage the sustainable development. Manjakkal et al. [91] presented an energy-autonomous system comprised of natural jute fiber-based supercapacitor (SC) and sensors (temperature and humidity) (Fig. 10c). The designed temperature sensor demonstrated a relative change in response of 0.23 % $^{\circ}C^{-1}$ from 24 to 35 °C and the humidity sensor displayed a sensitivity of 1.5 Ω/%RH (relative change of 0.20 %) up to 50%RH. The exhibited supercapacitor, which was created with eco-friendly and biocompatible components, could power jute-fiber based sensors, showcasing an appealing environmentally favorable option for uses including wearables, grain sacks and bags. As a substitute for the traditional nylon or polyester breather, jute/polyester hybrid breathing materials were created to cut down on the usage of synthetic polymers [92]. However, waste management is still a problem for breathers that have been scrapped. To investigate the potential for recycling discarded hybrid nonwoven breathers, a circular economy approach was presented [93]. The autoclave forming of carbon fiber-reinforced polymers was first facilitated by the use of hybrid nonwoven breathers. The used breathers were then recycled and utilized in three different ways, including directly as reinforcing material and in hybrid combinations with glass fibers and ramie fibers to create new composites (Fig. 10d). Jute fabrics were upcycled in a new efficient technique that produced a flexible transparent functional film (Fig. 10e) [94]. Jute fabrics were dissolved using ionic liquid as a green solvent to create translucent jute film, which can be recycled on average at a rate of 87.82 %. This clear renewable jute film can be transformed into a variety of useful products, including packaging materials, conductive films, and data storage devices. A debatable research topic is the exploitation of biomass and recycling of plastic trash. Composite materials made from the mixture of recycled plastic and biomass resources seem incredibly popular. A successful attempt has been made toward a unique formulation strategy by combining recycled polypropylene with woven jute fiber and pine needles to create hybrid laminate composites (Fig. 10f) [95]. The tensile and flexural strength of pine needle-filled jute fiber hybrid composites was found to be higher than that of solely pine needle-based composites based on mechanical behavior. With just a little loss in mechanical performance, the created composites have the potential to drastically minimize the use of plastic (by 40 %). This hybrid laminate composites may find economic appeal in a variety of non-structural household goods, including photo frames, paperweights and penstands.

It can be seen from the above discussions that jute fiber can be used as a substitute for high-performance fibers to synthesize composite materials with other functional substances, widely used in electromagnetic shielding, sensing, packaging and medical fields. The reinforcement materials, adsorption materials, and flame-retardant materials of jute fibers are currently research hotspots. How to apply high-

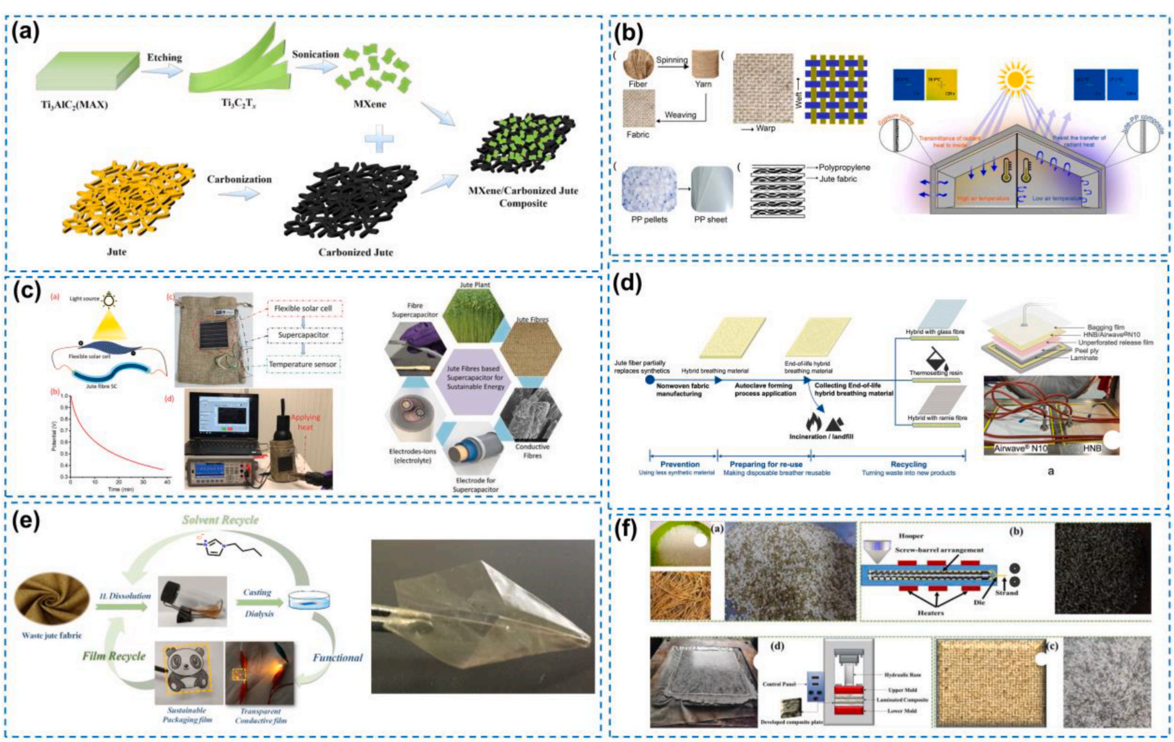

Fig. 10. Energy use and upcycling of jute fiber composites: manufacturing of MXene/CJ EMI jute composite (a) [90], jute–PP composite as thermal insulation in buildings (b) [96] and jute fiber composite as supercapacitors and sensors (c) [91], (d) strategical jute fiber composite manufacturing, application and recycling [93], (e) multiple recycle of jute film from jute fabric [94] and (f) fabrication of pine needle/recycled polypropylene/jute fiber hybrid laminates [95].

performance jute fiber composite materials to actual production processes is still an urgent challenge that needs to be solved.

5. Advances in kenaf fiber composites

Kenaf fibers are superior to synthetic polymer fibers in many aspects, including large aspect ratio, small specific gravity, good chemical characteristics, great mechanical qualities, large cellulose content, low thermal expansion rate and environmental advantages [97–99]. While kenaf fibers were initially used to make fabrics, ropes, cords and storage bags [100], they are now combined with other materials to create composites that are used in a wide range of industries, such as the construction, packaging and furniture industries [101–105]. Kenaf fibers are considered more economical as raw materials in polymer matrix composites due to their plentiful and affordable renewable resources [106–110].

5.1. Kenaf fiber transformed adhesives

A great interest has recently emerged in combination of kanaf fiber with biobased polymer to create a whole biobased composite (Fig. 11). A green, non-formaldehyde and efficient soybean meal/tannic acid/kenaf fiber composite has been developed (Fig. 11a) [111]; based on a bionic design, the redesigned kenaf fiber showed a rougher surface and more reactive groups, which solidly implanted in the soybean meal matrix. The final glue has outstanding adhesive strength and water resistance due to the solid mechanical interlocking effect and multiple chemical crosslinking capability. Wet shear strength dramatically increased from 0.41 MPa to 1.52 MPa in comparison to the soybean meal adhesive, while moisture absorption dropped from 10.1 % to 8.6 %. Liu et al. [23] has also modified kenaf fibers through a two-step procedure of calcium carbonate nanoparticle physical impregnation (PI) and N-cyclohexyl-2-benzothiazole sulfenamide chemical bonding (CB) to enhance the interfacial interaction with soybean meal matrix (Fig. 11b). The wet shear strength of the (PI-CB) kenaf fiber-reinforced soybean meal adhesive improved from 0.38 MPa to 1.64 MPa in comparison to the control one. In order to create a high-strength, water-resistant, mildew-proof and flame-retardant soybean meal composite, Liu et al. [112] has further used hierarchical kenaf fibers that were phenylboronic acid-tethered as the reinforcing agent (Fig. 11c). With their strong mechanical interlocking and chemical crosslinking with soybean meal matrix, the hierarchically rough surfaces and reactive sites of kenaf fibers along with their entanglement and interpenetration gave the kenaf fiber/soybean meal composite an exceptional water-resistant and bonding strength. The wet shear strength of the plywood produced by the resulting composite adhesive increased by 391.7 % to 1.18 MPa.

A unique kind of mineral-functionalized kenaf fiber-based hybrid soy protein composite adhesive (SPA) has also been attempted to address unfavorable cure rate and weak adhesion qualities of protein-based non-formaldehyde adhesives [113], in which the kenaf fibers were in-situ anchored by highly heat conductive hexagonal boron nitride particles (Fig. 11d). The mineral-functionalized kenaf fiber addition was able to lower the curing temperature, speed up the curing process, and increase the adhesion and water resistance of the hybrid SPA by bridging the link of functionalized fiber hybrids. The created plywood samples had a wet shear strength of 1.57 ± 0.11 MPa, which was a relatively strong bonding strength. The environmentally friendly kenaf fiber/soybean meal composite adhesives offer a fresh alternative to dangerous formaldehyde-based adhesives and help promote the use of agricultural and forestry byproducts in real-world applications. The surface modification of kenaf fibers or their combination with other functional particles provides a new design strategy for biomass-based adhesives, which play an important role in expanding the industrial application of these bioadhesives.

5.2. Kenaf fiber composites in automotive components

One of the major challenges for kenaf fiber composites is the inadequate interfacial adhesion between the fibers and the polymer matrix, which therefore has gradually attracted attentions across the sectors, especially, the global automotive industry (Fig. 12). A chemically treated woven kenaf fiber/unsaturated polyester/silver nanoparticles nanobiocomposite was developed using a compression molding method (Fig. 12a) [105]. The mechanical properties of nanobiocomposites were greatly improved and their capacity to absorb water was decreased by the addition of silver nanoparticles and chemical treatment of kenaf

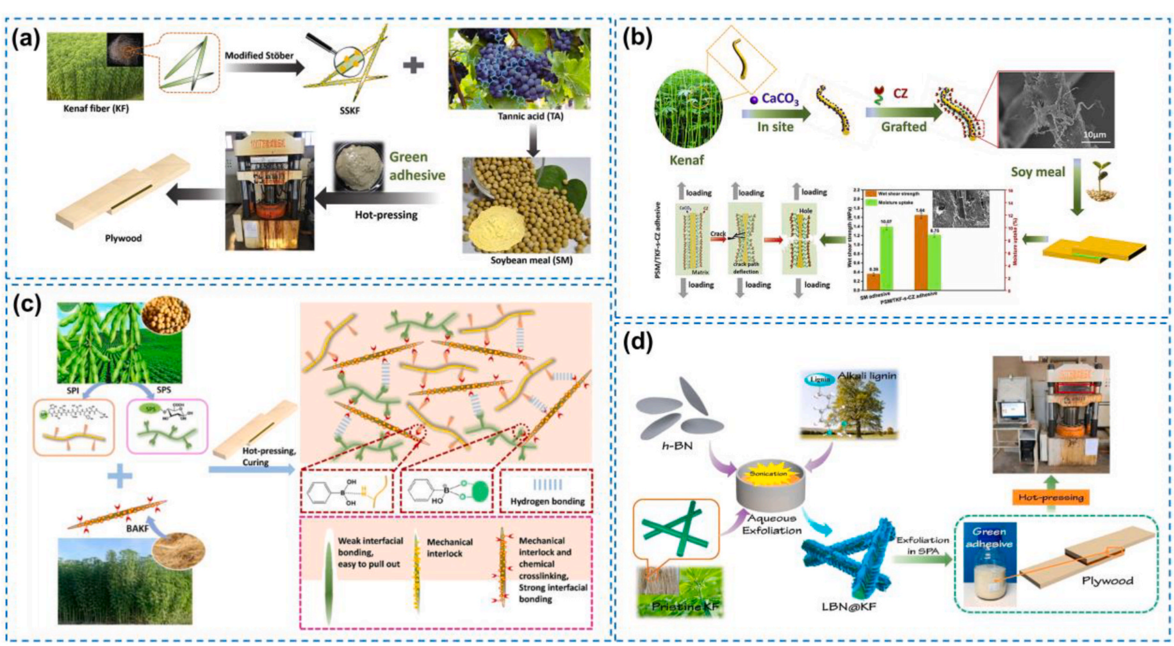

Fig. 11. Kenaf reinforced soybean based composite adhesives: Fabrication of kenaf fiber/soybean meal/tannic acid composite adhesive used for plywood (a) [111] and CI-CB kenaf fiber-reinforced soybean composite adhesive (b) [23], (c) mechanism of mechanical interlock and chemical crosslinking of kenaf fiber/soybean composite adhesive [112] and (d) fabrication of mineral functionalized kenaf fiber/soy protein/boron nitride composite adhesive used for plywood [113].

Fig. 12. Improved kenaf fiber composites through surface modification: Fabrication of kenaf fiber/unsaturated polyester/silver nanoparticles nanobiocomposite (a) [116], kenaf/RPET composites (b) [114], ZnO doped kenaf fiber-reinforced biocomposite in automotive application (c) [115] and vacuum bag molded kenaf fiber-reinforced biocomposites (d) [117].

fibers. The created nanobiocomposites could be a good substitute for external and interior automobile parts like door panels and dash boards as well as seat frames, central consuls and side panels. Owen et al. [114] introduced recycled and virgin polyethylene terephthalate (PET) polymeric composites reinforced with chemically modified kenaf fibers by surface coating treatment technique for automotive applications (Fig. 12b). Alkaline and epoxy coating surface modification techniques were used and the recycled polyethylene terephthalate (RPET) bottles were ground into flakes and melt-mixed with 10 wt% of short kenaf fibers in a twin-screw extruder and compression-molded at 240 °C optimized temperature. In comparison to untreated (KF/RPET and KF/VPET) composites, both treated (TKF/RPET and TKF/VPET) composites were more thermally stable, had greater mechanical properties and displayed a strong fiber/matrix adhesion without any obvious signs of fiber degradation. The prospective uses of these composites include engineering applications as well as those related to the automotive industry, such as insulation and interior car parts. A ZnO doped kenaf fiber-reinforced biocomposite has also been developed and evaluated to replace the commercial automotive glass-fiber sheet molding compound (GF-SMC) because of its outstanding performance and green characteristics (Fig. 12c) [115]. The mechanical characteristics, energy use, and life-cycle environmental effects of the created kenaf fiber biocomposite were superior to those of commercially available GF-SMC (Meridian's SLI 323IF). To further improve the mechanical and waterproof properties, an enhanced kenaf fiber-reinforced biocomposite through a vacuum bag resin transfer molding process after impregnating magnesium hydroxide to kenaf fibers was further attempted [108] (Fig. 12d). The modulus of rupture and tensile strength of modified composites dramatically increased by 73.9 % and 54.6 %, respectively. It can be concluded that the similar qualities to automotive GF-SMC and significantly reduced environmental effect and energy consumption make this modified kenaf fiber-reinforced biocomposite great potential in the

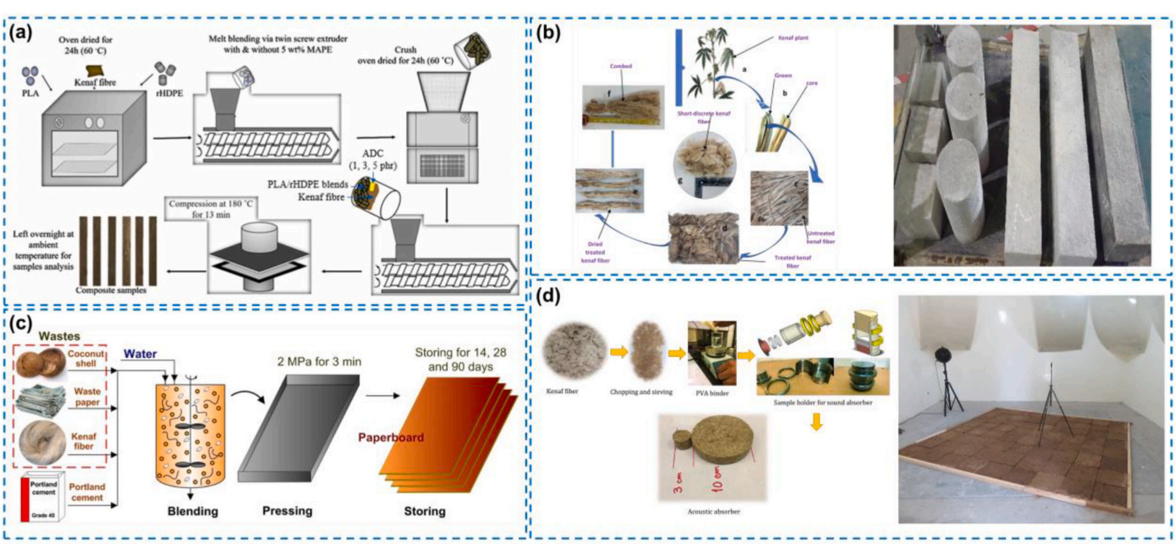

Fig. 13. Kenaf fiber based building materials: (a) extruded PLA/rHDPE/kenaf fiber foamed biocomposite (a) [118], kenaf fiber cementitious composite (b) [119], kenaf fiber reinforced cementitious paperboard (c) [121] and kenaf fiber acoustic building panels (d) [120].

manufacturing of automobiles.

5.3. Kenaf fiber based building composites

The progress of kenaf fiber based composite building materials has been substantial (Fig. 13). Compared to artificially synthesized composites, kenaf fiber reinforced composites have the advantages of lower density and lower cost, and can be used in construction projects to make escalators, doors, windows and floors. The poly(lactic) acid/recycled high-density polyethylene (PLA/rHDPE)/kenaf fiber biocomposites have been developed using an extrusion-compression molding method [118], achieving both lightweight and high-performance (Fig. 13a). In comparison to pure PLA and rHDPE, (90/10) and (70/30) (wt/wt)% compatibilized blends of PLA/rHDPE exhibited the improved flexural properties, up to 54–1549 %. This PLA/rHDPE/kenaf fiber biocomposites foam has a significant potential to replace conventional foamed materials used in interior construction because of its uniform porosity structure, lower density and better mechanical strength. A kenaf fiber-reinforced concrete (KFRC) composite has been reported (Fig. 13b); the biofiber has been considered a promising reinforcement to concrete with its environmentally friendly and negative CO_2 characteristic [119]. When kenaf fiber was added to concrete, the residual flexural strength marginally increased with an increase in exposure temperature up to 300 °C but decreased to 15 % at 800 °C. The degradation of fiber and concrete components at high temperatures could be a contributing factor in the strength reduction. Kenaf fiber has also been used to reinforce cementitious paperboard that can be a good substitute to particleboard for furniture and interior fittings (Fig. 13c). An increase of kenaf fiber (KF) to cement-paper composite resulted in a decrease in the density and the largest increase in tensile strength was achieved with a KF dosage of 2%wt cured for 28 days [111]. Taban et al. [120] prepared a porous absorbers made of natural kenaf fibers and investigated its acoustic behavior (Fig. 13d). The average sound absorption coefficient (SAC) for frequencies above 1250 Hz for samples of 40 mm thickness was found to be 0.95, while these values for samples of 30 and 20 mm thickness were respectively 0.85 and 0.7. Kenaf fiber composites have good sound absorption performance and have great prospects in noise control of buildings. As a renewable resource and characterized by natural degradation, kenaf fibers can reduce construction waste and promote sustainable development of human society. In addition to traditional industries such as the construction industry, kenaf fiber composite materials also have great consumption potential in other emerging markets, such as ceramic tiles, flower pots, trays and disposable daily necessities.

6. Advances in flax fiber composites

One of the earliest fibers to be extracted is flax, which is then spun and woven into clothing [122]. In addition to textile applications, flax fiber has recently drawn much interest from the energy, biomedical, automotive and environmental areas as a renewable material to enhance the performance of composites by using various technologies [123–126]. Owing to their unique qualities, which include being affordable, readily accessible and biodegradable [127,128], flax fiber also was chosen to fabricate car-door panels and retaining mats in the automotive industries [129,130].

6.1. Flax fiber based flame-retardant composites

In some respects, flax fiber-reinforced composites perform extremely similar to glass fiber-reinforced composites [131], this might be typically attributed to its low density and robust mechanical properties [132–136]. Nevertheless, these promising composites are hampered by the intrinsic flammability of flax fibers, which could prevent flax fiber composites from a variety of applications, including those requiring the combination of mechanical performance and fire safety in the railway, aviation and marine sectors. Flame retardants may be added to the polymer matrix to reduce the flammability of the flex composite (Fig. 14). Klingler et al. [137] fabricated a flax fiber reinforced thermoset composite by a compression molding method (Fig. 14a). Flame retardant coating of this formulation on medium density fiberboard (MDF) showed outstanding fire protection and heat isolation properties, which was demonstrated by higher weight retention (93 %) compared to the blank MDF (26 %), due to the excellent intumescent nature of the char formed during fire test. The layer-by-layer assembly method was also used to modify flax fibers in order to create PLA/flax bio-composites that are both flame retardant and mechanically robust (Fig. 14b) [138]. A quadruple-layer coating of chitosan, sepiolite and ammonium polyphosphate was applied to the flax fibers. Only 2.5 % significantly increased the flame retardancy and fire safety of the prepared composites, as shown by the limiting oxygen index (LOI) value of 25.3 %, noticeably decreased flame spread rates, and reduced maximum average and peak heat emission rates during cone calorimetry, −33 % and −30 %, respectively. Layer-by-layer (LBL) self-assembly technique has a wide range of applications in the field of flame retardant, but it requires repeated assembly to produce the necessary flame retardancy, which increases the time requirement and complexity of the process and limits future application. In order to solve the problem, phytic acid and ammonium alginate were used to create a totally bio-based flame--retardant system that gave flax fabric exceptional flame retardancy with just one biolayer of assembly (Fig. 14c) [139]. The peak heat release rate, total heat release, peak smoke release rate and total smoke release of the flame-retardant treated flax fabrics composite were decreased by 65.1 %, 52.7 %, 64.4 % and 32.1 %, respectively. Taibi et al. [140] presented the functionalization of flax fibers using a phosphorus-containing monomer to enhance flame retardancy (Fig. 14d). Pre-irradiation grafting was used to modify flax fibers, which required radiation treatment using an electron beam. A phosphorus-based dimethyl(methacryloxy)methyl phosphonate was used as a flame retardant grafting agent. The amount of phosphorus in the treated flax fiber composite largely determined its thermal stability and flammability. A flax fiber reinforced phenolic composites was developed by adding dimethyl methylphosphonate (DMMP) and nano-sized montmorillonite (MMTs) modified phenolic resin (Fig. 14e) [141]. Pretreating flax fiber with DMMP is a quick and easy way to increase the flame retardancy. The addition of MMTs to the phenolic resin aided in the production of additional carbonization layers inside the composites during burning, which worked in concert with the DMMP to suppress flame. It is apparent that inherent characteristic of flax fiber and the composite assembly with flame retardant are the key element that affects the flame-retardant properties of flax fiber composites. The development of efficient assembly method and new modification process is of importance for the further development and application of flame retardant flax fiber composites in some critical industrial sectors, e.g. transportation.

6.2. Flax fiber composite as reinforcements

Flax fibers have enormous promise for use in structural composites as sustainable and renewable reinforcing materials, however, mechanical properties remain challenging. The high safe and reliable requirements in some applications, e.g. outdoor structures, have led to the development of special flax fiber composites (Fig. 15). A flax/polypropylene composite stainless steel hybrid laminate was produced, and the hydrothermal and thermal ageing performance was examined (Fig. 15a) [142]. The hybridization of flax/polypropylene composite with stainless steel sheets provided a considerable improvement in bending and impact properties. The hybridization of flax fiber with synthetic fibers can also achieve some specific characteristic, e.g. a novel tri-directional carbon-flax-aramid fiber reinforced composite (3D-CFAFRP) (Fig. 15b) [143]; using flax fibers instead of carbon fibers resulted in almost all the specific properties of the 3D-CFAFRP composites being higher than

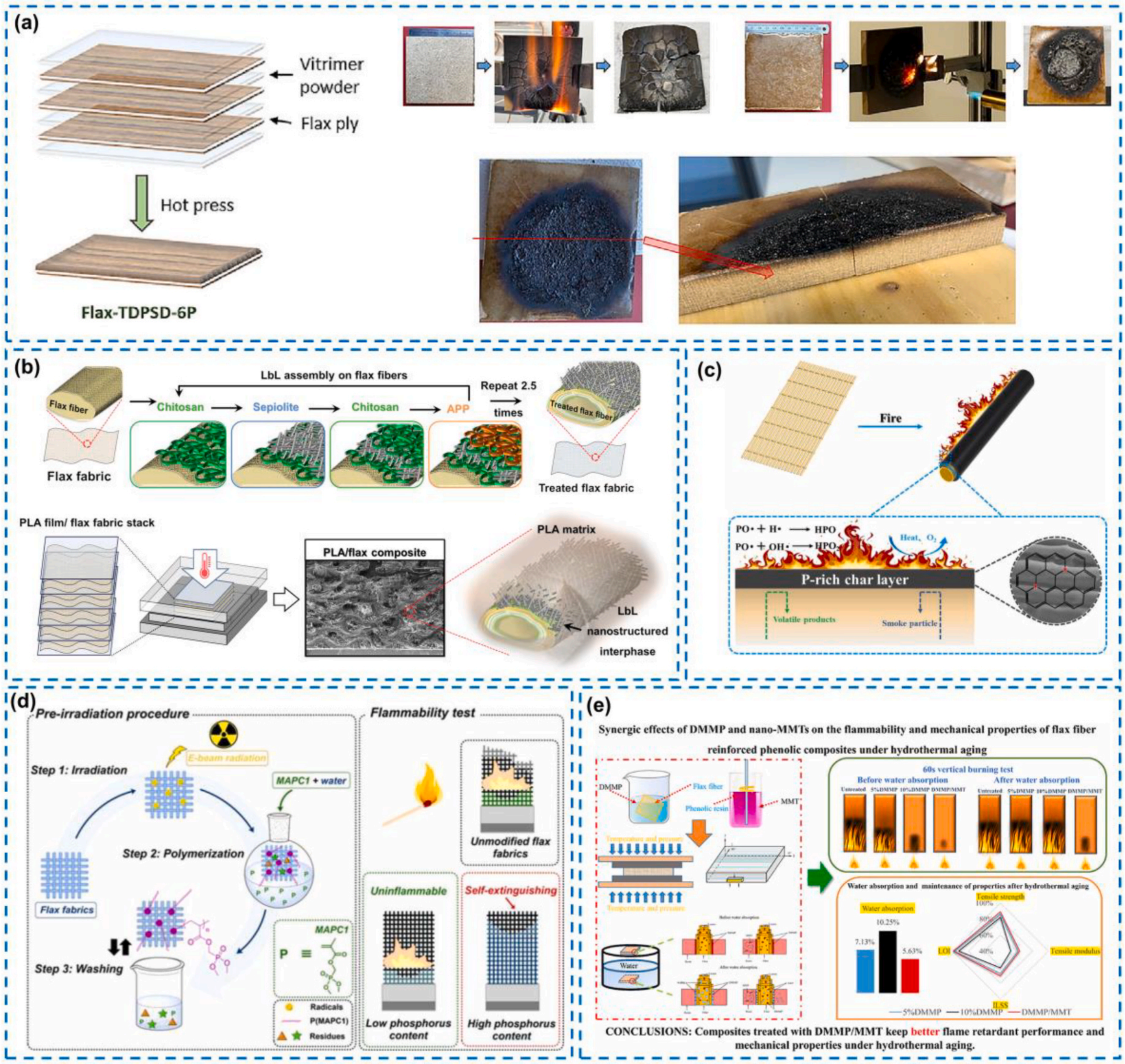

Fig. 14. Development of fire retardant flax fiber composites: (a) flame retardant coated flax fiber composite (a) [137], LBL assembled fire retardant biocomposite (b) [138], flame-retardant mechanism of the phytic acid and ammonium alginate system (c) [139], flame retardant flax fiber composite with pre-irradiation grafting of a phosphonate monomer (d) [140] and synergic effect of DMMP and MMT on the flammability and mechanical properties of flax fiber reinforced phenolic composites (e) [141].

those of 2D-CFRP composites. Additionally, owing to the use of flax fibers, 3D-CFAFRP composites also have the potential to be inexpensive and environmentally beneficial. Woigk et al. [144] exploited discontinuous carbon fibers in rheologically modified inks to controllably reinforce flax-based laminates composite in specific directions (Fig. 15c). By using tape casting or 3D printing techniques, the carbon fibers were integrated directly into the pre-aligned flax structures. Controlling the relative orientation of the hierarchically structured carbon and flax fibers greatly improved the elastic modulus, strength, and damping behavior of the flax-based composites. It demonstrates the possibility of hierarchical structure in enhancing the mechanical performance of flax-based composites by mixing reinforcing materials of various length scales with easily accessible production procedures. A chitosan-flax composite by using an aqueous casting technique was also reported (Fig. 15d) [145]. Applying initial low molecular weight (LMW) solution impregnation and then casting with LMW chitosan solution produced a strong flax fiber-chitosan interface, which was linked to porosity and efficient fiber impregnation. The low density of the chitosan-flax composites gives a competitive edge when used as a replacement for particle board or plywood in suspended ceilings, furniture compartments, and sporting or recreational equipment. Flax fiber composite materials produced with these commingled flax/poly-(propylene) preforms contain few cortical residues and show a significant degree of fiber individualisation [146]. In addition, when the fiber volume fraction is 36 %, these composites exhibit high Young's modulus and a stress at break of 24 GPa and 194 MPa, respectively. Optimisation of textile preforms play a crucial role in the development of high-performance bio-based composites materials.

The research of flax fiber reinforced composites has made great progress in recent years. The application fields continue to expand; the advanced processing methods, physical or chemical modification of flax fiber reinforced composites need to be further explored to improve their mechanical properties. In addition, understanding the biodegradation mechanisms and reliability and establishing an appropriate evaluation system for the composites are highly required in practical points of view.

6.3. *Flax fiber fabric composites*

Flax fabric composites have also attracted great interest recently (Fig. 16). Special textiles are highly required for personal thermal and

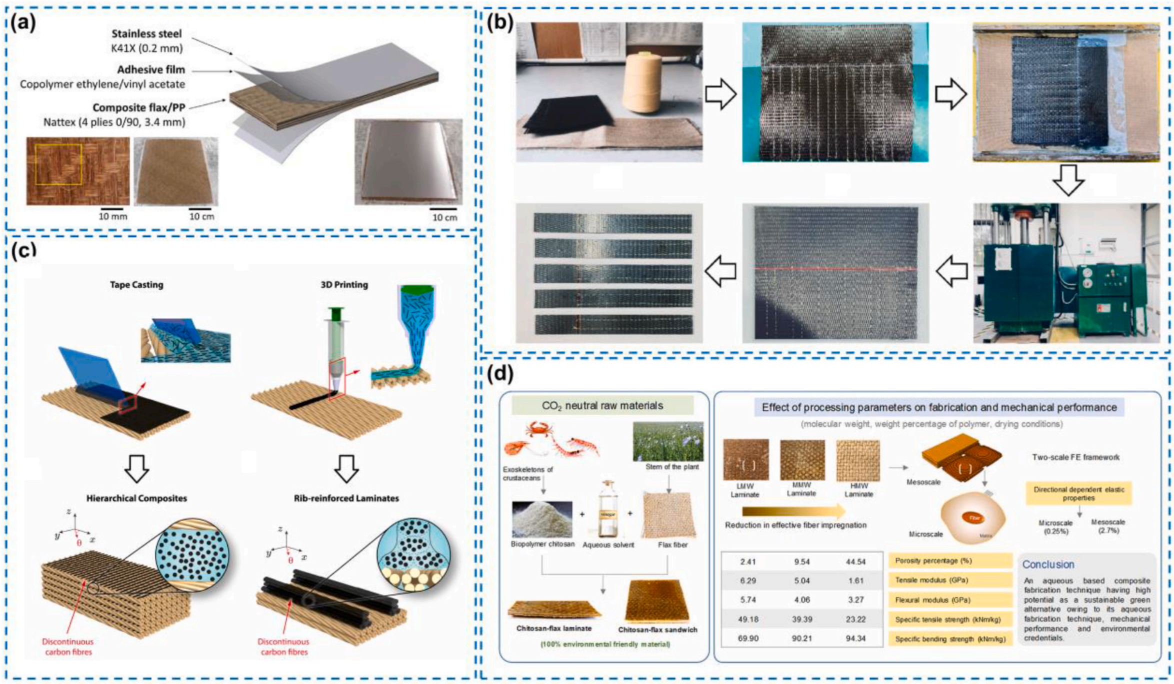

Fig. 15. Approaches of enhancing mechanical properties of flax fiber composites: formulation of (a) metal/flax/polypropylene composites [142], (b) 3D-CFAFRP composites [143], (c) flax-carbon fibers composites [144] and (d) chitosan-flax composites [145].

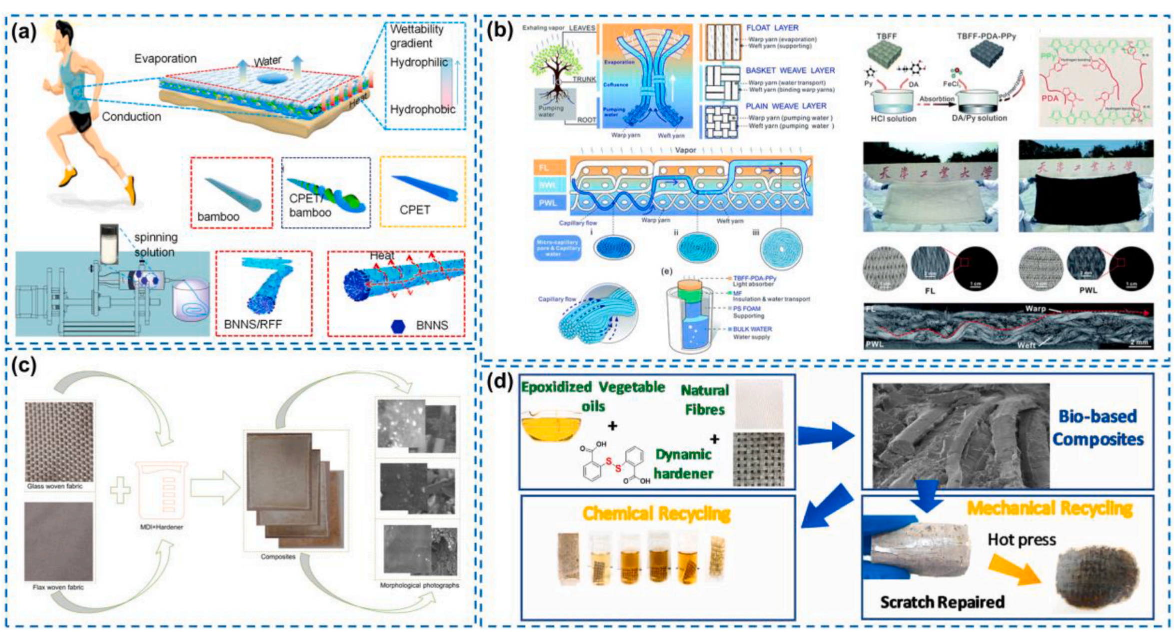

Fig. 16. Functionalized flax fiber composite fabrics: boron nitride nanosheet/regenerated flax fiber and dual-cooling composite fabric (a) [147], tree-shaped biomimetic flax fabric (b) [148], flax/glass woven fabric reinforced laminated composites (c) [149] and flax fibers/bio-epoxy resins bio-composites fabrics (d) [150].

wet comfort during human activities. A green, degradable, hygroscopic cooling material and dual-cooling composite fabric has been reported consisted of cool polyester (CPET) yarn (inner layer), CPET/bamboo composite yarn (middle layer) and 60%wt boron nitride nanosheet/regenerated flax fiber (outer layer) (Fig. 16a) [147]. This dual-cooling composite fabric offered a cooling sensation when touched thanks to its high one-way water transport index (468 %), extremely high evaporation rate (0.3818 g h^{-1}), and other characteristics. This work offers a method for creating ecologically acceptable flax fiber-based composite fabric as well as a simple method for creating cooling textiles for managing human health. Inspired by the natural transpiration process of trees, Li et al. [148] created a 3D hierarchical tree-shaped biomimetic flax fabric (TBFF) using an ordinary loom with a float layer, basket weave layer and plain weave layer (Fig. 16b). The fabric demonstrated directional water transport properties along the continuous warp yarns of the fabric. The hierarchical micro-capillary pores of yarns and macro-interlaced pore structures between the warp and weft yarns in this modified composite displayed broadband light absorption, high-performance water supply, high evaporation area, and simple steam escape.

The development of a green fabric composite was reported by Hasan et al. [149] using methylene diphenyl diisocyanate resin with flax and synthetic glass woven fabrics as reinforcement (Fig. 16c). The combination of 16.87 % flax fibers and 83.33 % glass fibers gave acceptable mechanical properties (tensile strength 69.63 MPa and flexural strength 147.7 Mpa). Mauro et al. [150] attempted flax fibers/bio-epoxy bio-composite fabrics. To create recyclable epoxy thermosets, the bio-epoxy resins based on five epoxidized vegetable oils were combined with 2, 2′-dithiodibenzoic acid (DTBA), an aromatic disulfide crosslinker with diacid activity (Fig. 16d). Flax fiber was used as bio-based reinforcement for these matrices. Resins and bio-composites could be recycled chemically and mechanically thanks to the networks' dynamic crosslinking. Additionally, the results demonstrated the potential for recovering flax fiber filler for the creation of second-generation bio-composites. In summary, flax fibers-based composite fabrics have a wide range of prospective applications in textiles and other emerging fields. However, the majority of the relevant studies are still in the early phases of development, and only a small number of trials have been carried out in real-world settings.

7. Advances in hemp fiber composites

Hemp fiber composite is one of the most successful industrialized modern natural fiber composites, especially in automotive industry [151–153] and significant efforts have been spent on fiber characterization, modification, nanocellulose, nanocomposites and structural hemp composites for various applications, e.g. construction, fabric, and bioplastic applications [154–160].

7.1. Hemp fiber foam/aerogel composites

Some of the most recent advances have also been achieved (Fig. 17): A colorimetric pH foam indicator by loading the natural dye anthocyanin onto hemp fiber (anth-foam) has been developed (Fig. 17a) [161]. Biomass-derived anth-foam had unique characteristic like nontoxicity, low density and high porosity. The porous nature of anth-foam led to a dramatical reduction of the colorimetric response time by 60 % when compared to film-based indicators. As NH_3 concentration rose to 250 ppm, the anth-foam showed a significantly increased color shift and outstanding cycling ability, preserving about 90 % of the initial colorimetric response over a number of cycles. These characteristics made the anth-foam a potential substance for real-world uses as a pH colorimeter. A super-elastic aerogel has also been reported consisting of hemp microfiber and nanocellulose aerogel. The microfiber was produced through an efficient and straightforward top-down method [162]. These fibers was then combined into an ultralow density nanocellulose aerogel utilizing the ice-templating method (Fig. 17b). These aerogels showed isotropic super-elasticity with densities as low as 2.1 mg cm^{-3}, as evidenced by their quick form recovery from compressive strain of more than 80 %. Lyu et al. [163] demonstrated the reuse of waste hemp oil by dissolution in a precooled NaOH/urea system to form porous aerogels (Fig. 17c). The hemp aerogel could remove 29.4 times its own weight of oil with a 1.5 % fiber content, and after 10 absorption/desorption cycles, 85.4 % of the initial absorption capacity was still present. The ultrafast oil absorption was completed within 0.048s. The particulate matter (PM) removal efficiency of the hemp aerogels was similarly quite high, reaching 94 % for both PM2.5 and PM10. The created waste hemp aerogel demonstrated excellent promise for resource recycling and environmental management. Waste biomass from hemp and birchwood was also used to create environmentally friendly nanocellulose foam (Fig. 17d) [164]. Foam materials with improved mechanical and thermal insulation properties could be produced by the freeze-drying technique, with controlled densities ranging from 2 to 36 mg/cc and porosities ranging from 99.7 to 99.9 %. Hemp fiber has demonstrated as potential material to formulate aerogel/foam composites. The geometry of hemp fiber could be designed to tailor the mechanical, physical and thermal properties of foam composites. It is anticipated that deep binding in electrical, acoustic, thermal, and dynamic mechanical properties will broaden the range of uses for hemp fibers in foam or aerogel composites, making applications in biomedicine, aviation, architecture and other fields a future research hotspot.

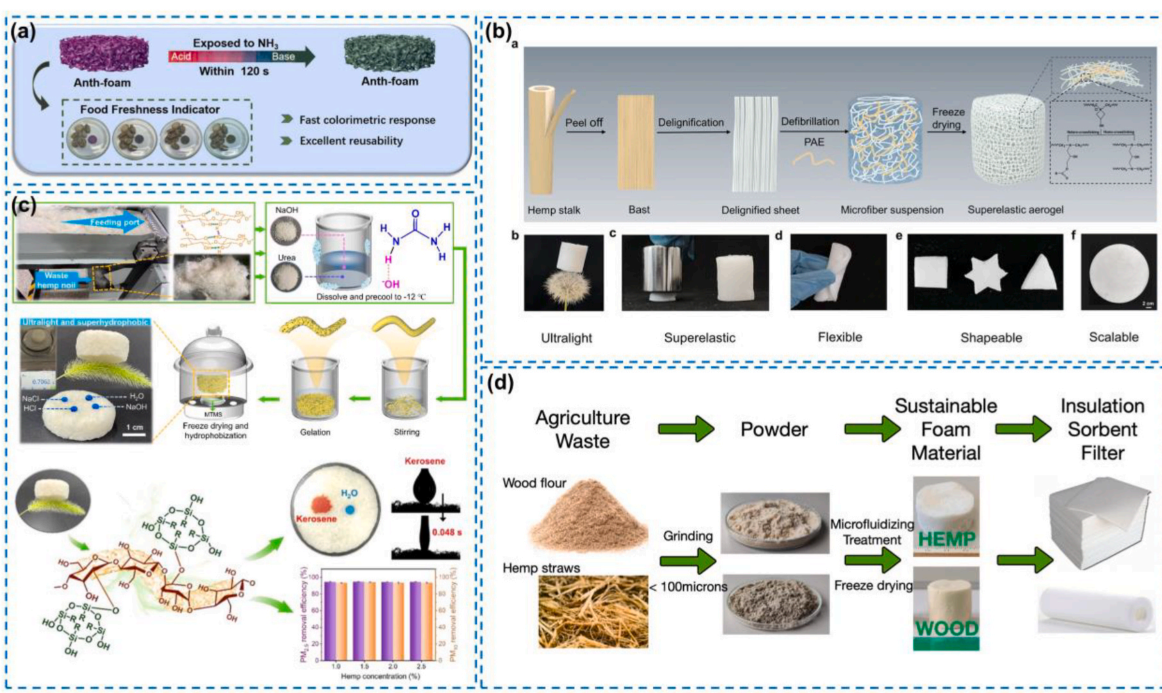

Fig. 17. Hemp fiber foam and aerogel composites: (a) hemp fibrous foam for colorimetric NH_3 sensing [161], (b) ultralow density hemp microfibers aerogel [162], (c) superhydrophobic hemp aerogel and its application [163] and (d) sustainable nanocellulose aerogel foam [164].

7.2. Hemp fiber based building composite materials

One of the most interesting developments for hemp fiber composites is cementitious composites (Fig. 18). Hempcretes have been employed as a binder (mostly lime) as an alternative to traditional mineral aggregates as part of a new bio-based material [165]. Fig. 18a showed two buildings with load-bearing hemp walls, constructed with prefabricated hemp concrete blocks (A) and cost compacted hemp concrete (B) as well as building blocks made with hemp concretes mixed with either a clay binder (C) or with NHL3.5 lime (D). (E) and (F) showed a non-loadbearing building with an internal timber structure with cast, non-rendered hemp-lime concrete. A micro-reinforced hemp and Spanish broom fibers cement mortar has also been reported (Fig. 18b) [166]. It must be noted that an increase of fiber content could lead to the formation of fiber bundles, which resulted in poorer mortar compaction around the fibers and more voids in the matrix, which reduced the mechanical properties of the mortar specimens. Numerous soil hemp concrete combinations were also attempted [167], each containing various ratios of clayey soil, sandy soil, minor amounts of cement, lime and hemp fibers (Fig. 18c). With more hemp fibers and clayey soil added to the tested concrete, the compressive strength of the material reduced, which may have been caused by the increase in porosity of soil concrete. The addition of clayey soil and hemp fibers resulted in a reduction of the ultrasonic pulse velocity (UPV). For concrete containing 20 % clayey soil, the use of hemp fiber reduced density and improved thermal and acoustic qualities while also increased water absorption by roughly 9 %. It is evident that most of the research on hemp fiber composites in the construction field focuses on the mechanical properties of materials, while the research on the fatigue properties of materials is scarce. In the future, more work is needed to understand the fatigue properties of hemp fiber cementitious composites, so as to expand the application of hemp fiber cementitious composites in construction and other fields.

7.3. Hemp fiber fabric composites

A wide range of design and production options for composite reinforcements are provided by textile technology, and hemp fiber fabrics have become of importance for biocomposites (Fig. 19). Thin hemp fabric/carbon hybrid laminates (1.8 mm thick) have been developed by using an ad-hoc manufacturing process for manufacturing impregnated woven hemp fabrics characterized by lightweight (area density ranging from 475 to 950 g/m^2) and located at the midplane of carbon laminates (Fig. 19a) [168]. Depending on the performance needed, one hemp ply can replace two carbon plies without degrading the structure's capacity to function and increase its sustainability. Liu et al. [169] reported a graphited knitted hemp fabrics as the basis for encapsulation-free, low-detection-limit and extremely permeable pressure sensors (Fig. 19b). The hemp sensors are endowed with desirable qualities such as superior permeability to air, water vapor and moisture, low detection limit (0.3 Pa), wide operating range (up to 500 kPa), outstanding cycle stability, and durability. Long-staple hemp and nylon fibers, blended yarns and their woven fabrics were also been produced (Fig. 19c) [170]. The performance of yarns and woven fabrics produced was significantly influenced by the proportion of hemp and nylon fibers in the blend. Moreover, as the hemp fiber content rose, both under dry and wet conditions, the tensile strength of yarns and textiles dropped. Further a highly aligned continuous hemp tape was created based on hemp sliver and used to prepare unidirectional composites with improved mechanical properties (Fig. 19d) [33]. At drafting multiple i = 2 and 30 % fiber content, the tensile and flexural strengths of composites reached 166.85 MPa and 207.68 MPa respectively, which were equivalent to those recorded for hemp fiber composites. The superior mechanical characteristic makes it potential for the applications in architectural, furniture and automotive panels. A novel composite material based on woven hemp fabric was developed which reinforce a thermoset polymer produced from birch bark [171]. This fully biobased composite has specific stiffness and strength equivalent to those of flax fibre-reinforced petroleum-based epoxy composites. Hemp fiber has excellent mechanical

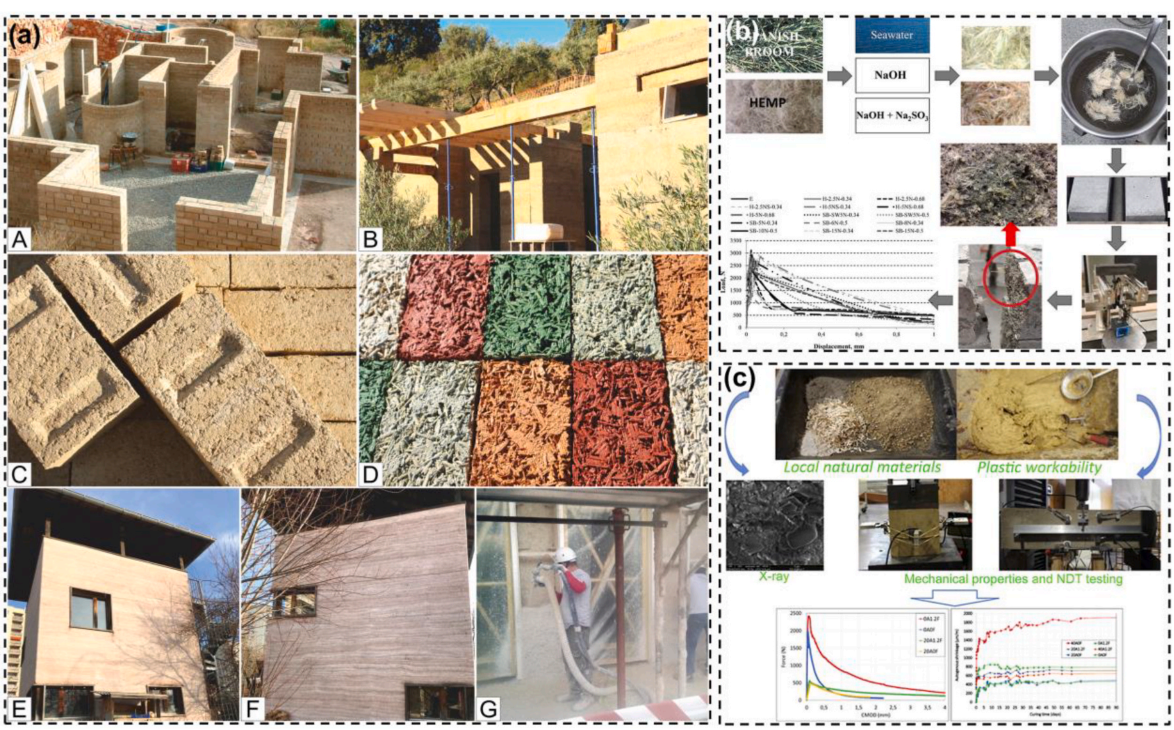

Fig. 18. Hemp fiber inorganic composites: (a) hemp concrete constructions built with premade building blocks [165], (b) treatment and concentration of Spanish broom and hemp fibers vs. mechanical properties of hemp mortars [166] and (c) design of a soil concrete as a new building material-effect of clay and hemp proportions [167].

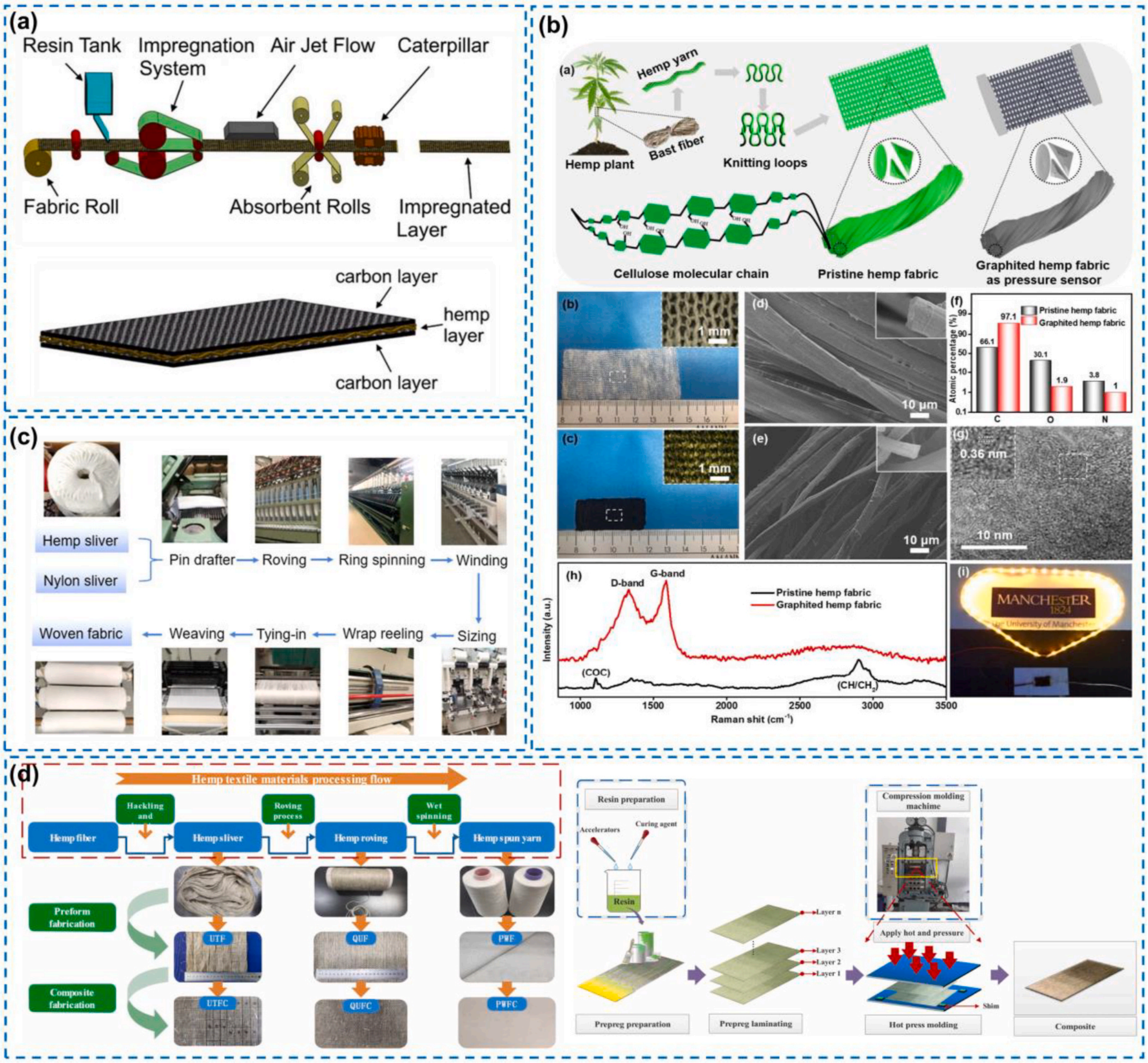

Fig. 19. Hemp fiber fabric composites: (a) hemp and carbon fabric composite hybridization [168], (b) graphited hemp fabric based sensors [169], (c) hemp based hybrid yarn and fabrics [170] and (d) aligned hemp sliver composite type [33].

properties, and its fabric composites have good mechanical properties with the benefit of environmental protection. However, the compatibility between hemp fiber and matrix is in general poor, which has an influence on the mechanical properties of fabric composites. The surface hydroxyl structure of hemp fiber can be effectively modified to control its hydrophilicity and hydrophobicity, so as to prepare fabric composites with superior performance.

8. Future perspective

The use of bast fibers in composites has been evidenced to achieve comparable mechanical strength and low environmental impact when compared to synthetic fibers. Currently, there is a strong growth opportunity for the usage of biocomposites, particularly in construction and automotive industries. With the rapid progress of material sciences, numerous advanced functional biocomposites emerge, e.g. nanotechnology enhanced biocomposites; the extended novel fibre and composite engineerings are directing breakthroughs not only on functionalities, but also on applications of bast fiber composites.

Despite their numerous potential features, bast fiber composites also present emormous hurdles in large-scale development. Some of the major constraints to the commercial application of bast fiber composites may include.

(1) Quality bast fiber supply remains major challenge. Bast fibre plants are exposed to various growing environments/climates, resulting in inherent characterisitc (defects). Novel efficient extraction processes are yet to be developed to obtain high-quality, high-yield bast fibers for the production of quality biocomposites.
(2) The compatibility of bast fibres with matrix is probably a single most important parameter for biocomposites, especially considering the hydrophobic matrix against hydrophilic bast fibres. Effective surface modification technologies and surface design of bast fibres are yet to be developed or enhanced.
(3) Hydrophilic nature of base fibre provides opportunities for various processes, from fibre production to functionalization. However, the moisture absorption and hence swelling of bast fibres in the composite presents in general challenging for the stability, durability and bonding strength of biocomposites.
(4) Biocomposites do in many cases not fully reflect property of bast fibres. The jouney from fibres to biocomposite engineering to performance in uses is required further elaboration. The should lead to further innovations in engineering, performance and application.
(5) Even if the bast fiber is recycled, the cost of recycling may be greater than the value of the composites due to the mix of

recycleable and non-recyclable constituents. A full biocomposite emerges as a potential opportunity for the relevant industries. Unique up-cyclying solutions may also be explored.

(6) Biocomposites provide potential for circularity development due to the unique merits of basl fibres, e.g. biodegradable and renewable nature of the raw materials. The strategy for such development is yet to be further developed.

If the limits described above are met or the opportunities are explored, the technological challenges confronting the commercial application of bast fiber products will be alleviated and major industrial impacts be achieved from bast fibre composites. The incorporation of nanocellulose into bast fiber reinforced composites could also confer additional beneficial properties.

9. Conclusions

The interest in high-value utilization of bast fibers has grown significantly in the recent years. Firstly, bast fibers showed various potential developments in the textile industry; the high strength and durability could lead to manufacture of tough and long-lasting functional textiles and textile products, such as clothing and industrial fabrics. Secondly, the combination of bast fibers with other materials has created functionalized composite materials for building construction and many other applications. These composite materials could exhibit good strength, fire resistance and other unique characteristics, e.g. impact, sound and thermal performance. Additionally, bast fiber generated biodegradable plastics have served as an eco-friendly alternative to traditional synthetic plastics, reducing negative environmental impacts. Moreover, bast fiber composites demonstrated broad application prospects in automotive manufacturing and aerospace industries with the lightweight nature and high strength making them suitable for producing vehicle body parts, interior materials and composite structures, achieving improved fuel efficiency and reduced carbon emissions, addressing environmental challenges and promoting sustainable transportation. Incorporating nanomaterials and enhancing fiber surface properties have led to enhanced functionalities of bast fibre composites, such as antibacterial, waterproof, and UV-resistant characteristics, thus broadening their application range. While bast fiber composites offer lightweight properties, and other impressive physical and mechanical characteristics, the dedicated practical applications demand even greater strength and toughness for various structural products. Moreover, scaling and commercializing bast fiber composites necessitate concerns related to production costs and sustainability.

CRediT authorship contribution statement

Shiyun Zhu: Writing – original draft, Conceptualization. **Junxian Xie:** Writing – original draft, Conceptualization. **Qianqian Sun:** Writing – original draft, Conceptualization. **Zhaohui Zhang:** Visualization, Data curation. **Jinming Wan:** Formal analysis, Data curation. **Ziyong Zhou:** Investigation, Data curation. **Junliang Lu:** Data curation, Conceptualization. **Jian Chen:** Data curation, Conceptualization. **Jun Xu:** Supervision, Conceptualization. **Kefu Chen:** Supervision, Conceptualization. **Mizi Fan:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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