Article

Hemp Fibres: Essentials, Composites or Nanocomposites and Technical Applications

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Abstract

In this article, we overview a very important type of natural fibre, namely, hemp fibre. We consider the exclusive structure, properties, modification, the composite or nanocomposite formation and exceptional application zones. Industrial hemp fibres have been commonly developed and possess high cellulose amounts. The long hemp fibres can be termed bast or flax fibres. Hemp fibres are eco-friendly, and have light weightiness and stiffness properties. Consequently, to enhance the use of hemp fibres at engineering level, research has focused on improving the mechanical or thermal and high-tech features of these fibres. In doing this, the surface modification or treatment of hemp fibres has been notably considered. The modified fibres have been found valuable for developing certain derived materials such as polymeric composites and nanocomposites in particular. Consequently, including hemp fibres as additives in composite or nanocomposite matrices has been explored for manufacturing high performance ecological, recyclable, biodegradable and sustainable materials. Application areas identified for the hemp and related composites or nanocomposites include the synchrotron and neutron scattering, water treatment aiming dye removal, automobiles, textiles and construction. However, there is insufficient literature on these technologically important fibres and ensuing materials. Comprehensive future efforts may better resolve the challenges regarding reproducibility and long life-cycle high-tech applications of hemp fibres.

Keywords: hemp fibre; composites; nanocomposites; surface treatment; dye removal; automotive; synchrotron

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1 Introduction

For decades, natural fibres have been used for emergent environmental, degradable and recyclable materials [1]. Natural fibres have been adopted in wide ranging applications including automotive, construction, textiles and packaging. Hemp fibres have been explored as important natural fibres for various technical purposes [2]. Hemp fibres are usually extracted from the stem of the hemp plant. Fig. 1 shows a typical example of grown hemp vegetation and the texture of the leaves.

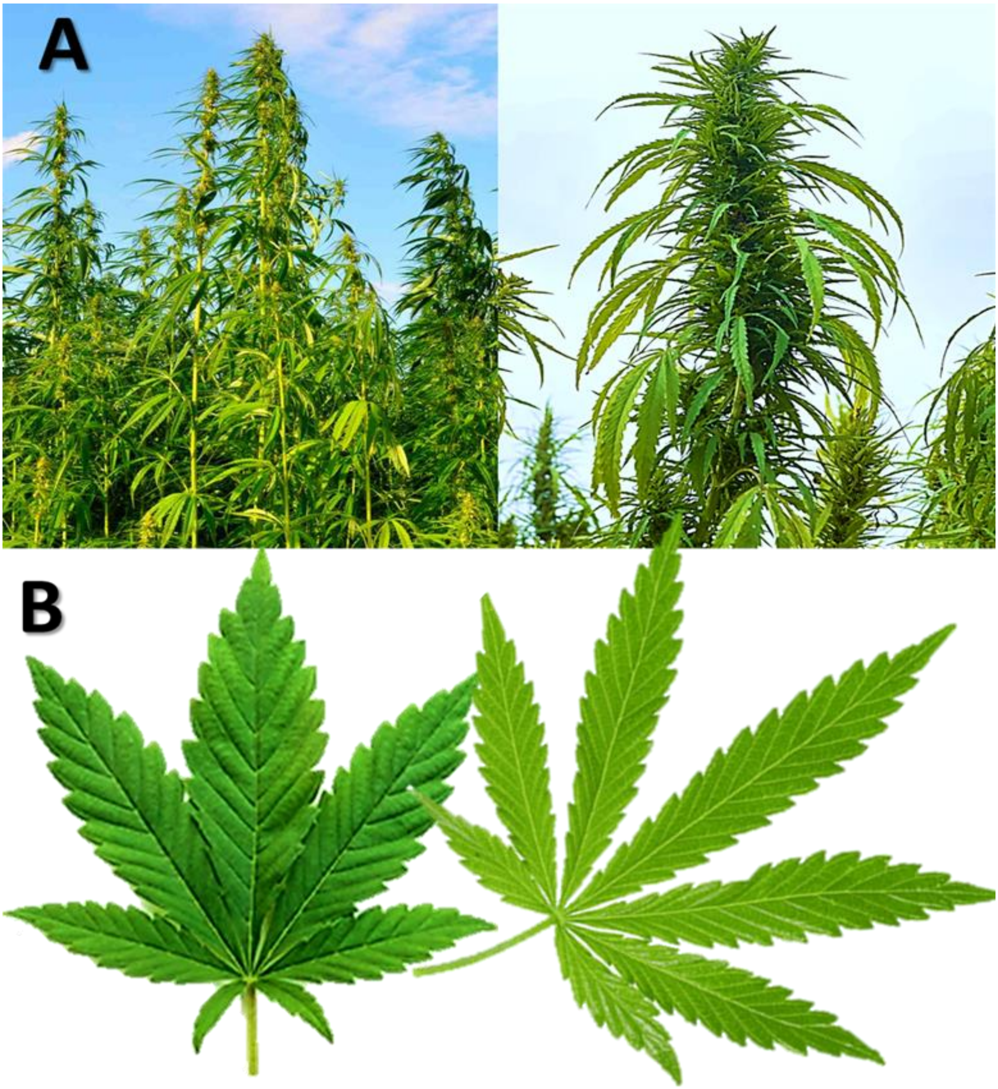

Fig. 1. (A) Typical hemp crops. (B) Hemp leaves.

Similar to other natural fibres, hemp fibres have been modified to attain advanced properties and performance [3]. Hemp fibres have been applied as reinforcement in composites and nanocomposites [4]. Here, thermoplastics and thermosets have been used as matrices for the hemp fibres. Surface functional hemp fibres have been found to develop better matrix-nanofiller interactions, interface formation, and optimum hydrophilicity properties. The surface alterations of hemp fibres have been carried out through physical, chemical, biological or other routes [5]. Using non-hazardous environmentally friendly methods have been preferred in this regard. The adapted hemp fibres have led to substantial enhancements in the strength and other characteristics of the polymer matrices. The applications of hemp fibres and related materials were observed in numerous applications such as radiation interaction, water purification, vehicle parts, textiles and other uses [6], [7].

Hemp fibres contain important bioactive molecules or compounds; *Cannabis Sativa* L. in particular has been used in the biomedical sector [8]. Cannabinoids, flavonoid, glycosides, lactones, flavonoids, polyphenols and esters have been observed in hemp fibres [9]. Out of these, cannabinoids or cannabidiols have been found effective as antibacterial or antioxidant activities. The composition of hemp extract may vary depending on the place of growth, conditions and plant age. Usually, the monoecious type of crop has been found useful for pharmacological interest [10]. The quality, composition and end application of hemp fibres may rely on the hemp fibre extraction technique [11]. In addition, the strength and flexibility of hemp fibres depend on the fibre extraction techniques [12], [13]. Properly extracted hemp fibres usually possess high strength and Young's modulus of 550–1 110 MPa and 30–70 GPa, respectively [14]. Like flax or jute fibres, hemp fibres have been studied for biological properties [15]. Consequently, hemp fibres reveal antimicrobial and antibacterial activities because of the constituents [16]. Extracted hemp fibres and modified hemp fibres have been used for antibacterial purposes. The presence of cellulose (an important biopolymer) based main chain in hemp fibres is found beneficial for biomedical applications.

Sustainability aspects of hemp fibres have been explored in the literature [17]. To minimise the global warming effect and carbon dioxide emissions, renewable resources have been researched to cause carbon negative effects [18]. *Cannabis sativa* L. has advantages of low growth cost, a rapid growth cycle, and efficient carbon negative conversions. Consequently, the growth of hemp fibres has been found to minimise the global warming effects affecting living beings and the environment. More sustainable applications of hemp fibres have been investigated for technical industries such as the paper industry, textiles, the beverage industry, biofuels, and the biomedical industry. [19]. Hemp-based biofuel can be an ecofriendly substitute of petroleum fuels for heat and energy for transportation and industries [20]. Hemp fibres can be beneficially used as ecological hemp concretes [21]. These materials possess fine insulation features, moderate load-bearing capability, and strength properties. Synthetic cement is usually not environmentally friendly owing to its continuous carbon dioxide emissions. Building materials that are based on hemp cement can be very advantageous for sustainability purposes [22]. Along with cotton, hemp fibres can contribute to the formation of eco-textiles applications [23]. Using hemp fibres in modern industries may therefore subsidise an ecologically safe and sustainable contribution to the environment, the economy and the world [24].

In this state-of-the-art article, we offer an impression on the progresses in the field of hemp fibres. It has been observed that surface functionalisation of these fibres may enhance the matrix-fibre interfacial bonding and resulting mechanical, thermal and other physical properties of the resulting composite materials. Forthcoming research in this field may reveal several exciting application areas of the hemp fibres and derived materials.

2 Hemp Fibres

The hemp plant (mostly *Cannabis sativa*) is low-priced, contains natural fibres, and can be grown worldwide in different regions [25], [26]. The long hemp fibres are often known as flax or bast fibres. The history of hemp fibre relates to several centuries back with the development of ancient ropes and paper [27]. Among their common uses is the extraction from the plants for the paper and textile industries [28]. Hemp fibre is one of the strongest found natural fibres and can therefore be applied as filler or reinforcement in the composite materials. The specific stiffness of hemp fibres has been found comparable to that of glass fibres [29]. A stem of hemp plant usually comprises cellulose, hemicellulose, lignin and pectin [30]. The phloem of the hemp plant has secondary bast fibres. Fig. 2 shows the structure and morphology of hemp macrofibres, microfibres and nanofibres. Studies on the cross-sectional structure revealed the presence of hexagonal cells in the hemp fibre [31]. The micrographs of transverse sections of hemp were studied using cryomicrotome both before and after ultraviolet (UV) irradiation [32]. A hemp fibre, therefore, has a multi-cellular structure with a high cellulose content responsible for enhanced structural properties [33]. For the separation of the hemp fibre from its plant, an ecofriendly microbial procedure is widely used (retting process) [34]. Consequently, the extracted hemp fibres have been used for numerous purposes and acid- or base-treated hemp fibres were developed to attain the further improved properties [35]. Table 1 presents some common benefits and drawbacks of materials that are based on hemp fibres.

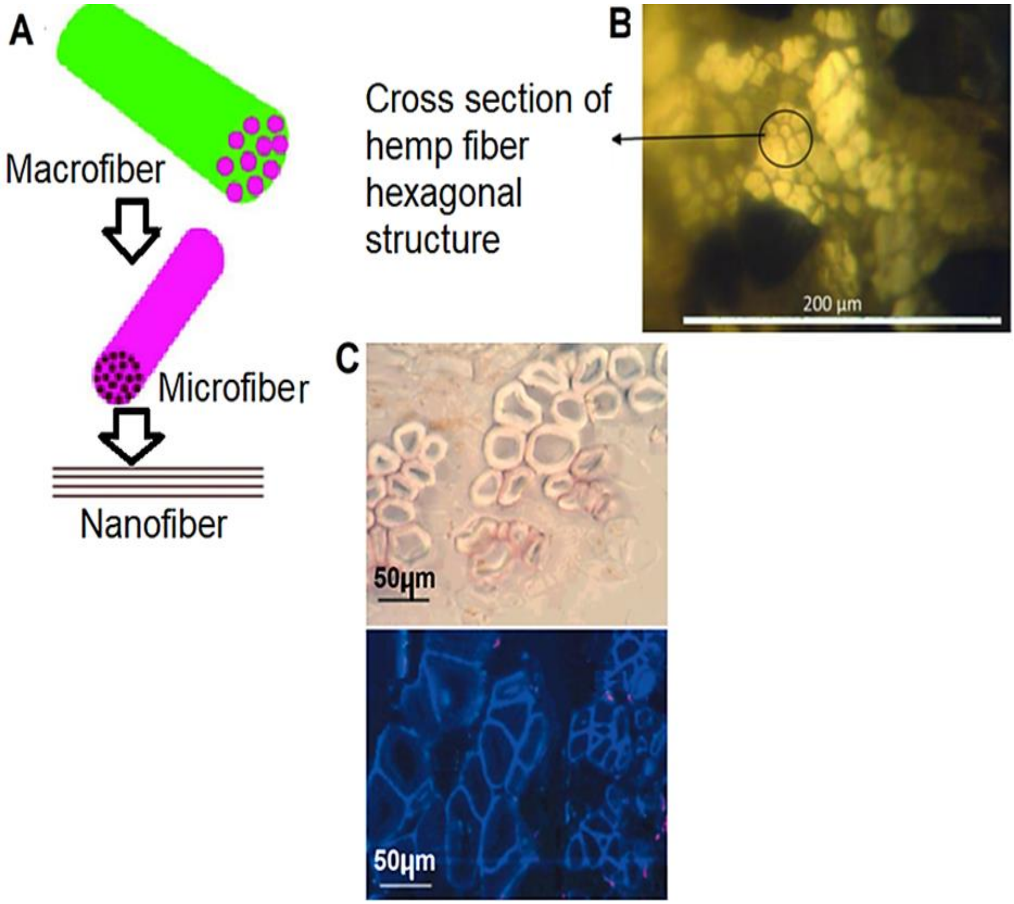

Fig. 2. Structure of hemp fibre: showing (A) microfibres to nanofibrils; (B) cross-sectional view of hemp fibre [31]; and (C) micrographs of transverse sections of hemp stems using a cryomicrotome, with and without UV lamp exposure [32]. Reproduced with permission from ACS.

TABLE 1
BENEFITS AND SHORTCOMINGS OF HEMP FIBRE AND RELATED MATERIALS

Benefits	**Drawbacks**
Low density Cheap production Fewer health risks while formation Lower costs than those of several synthetic fibres Ecofriendly until the end of life High specific stiffness/strength High thermal stability Acoustic features	Lower durability in processing when compared to synthetic fibres Moisture absorption can be problematic Lower mechanical, thermal and other properties than those of synthetic fibres Sensitivity towards flame, microbials, and UV irradiation In composites, non-modified hemp fibres have weak matrix-fibre interactions

The compositions of hemp and other plant fibres are given in Table 2 [36]–[38]. According to a comparative analysis, hemp fibres possess a high level of cellulose and hemicellulose, with a lower percentage contents of lignin and pectin. The fibre extraction processes for these fibres have been carried out through retting, breaking and hackling. The retting process is usually carried out for 1–6 weeks. During retting, compounds such as pectins may easily break down through bacterial and fungal actions. The hackling process is often used for separating and straightening the natural fibres.

Hemp fibres have been studied as raw green hemp fibres, hemp shives, and retted hemp fibres. Raw green hemp fibres possess a complex chemical structure with cellulose up to 72%, hemicellulose about 19%, lignin up to 5%, and minerals about 4% [39], [40]. The hemp shives possess lignin up to 25% and cellulose up to 40%. The retted hemp fibres are brittle and contain cellulose of about 70–74% due to pectin extraction in water phase [41]. The composition may vary according to the retting processes used for extraction and the type of hemp fibres (Table 3) [42]. In all the plant fibres, the amounts of cellulose, hemicellulose, lignin, and pectin may slightly decrease by ~ 1–2% during the extraction processes.

TABLE 2
A SIMPLE COMPARISON OF CHEMICAL COMPOSITION OF DIFFERENT PLANT-BASED NATURAL FIBRES

Fibre	Cellulose %	Hemicellulose (%)	Lignin (%)	Pectin (%)	Wax (%)	Ref.
Hemp	70–74	18–22	3.7–5.7	0.9	0.8	[36]–[38]
Flax	71–79	19–21	2.2	2.2	1.7	[36]
Jute	61–72	14–20	12–13	0.2	0.5	[36]
Kenaf	31–39	15–19	21.5	–	–	[36]
Wheat	29–51	26–32	16–21	–	–	[37], [38]
Rice	28–48	23–28	12–16	–	–	[37]
Oat	30–48	27–38	16–19	–	–	[38]
Bamboo	26–43	30	21–31	–	–	[37]
Banana	63–68	19	5	–	–	[36]
Cotton	83–94	5.7	–	–	0.6	[36]

TABLE 3
CHEMICAL COMPOSITION OF HEMP FIBRE EXTRACTED FROM DIFFERENT HEMP VARIETIES (BENIKO, WOJKO, TYGRA AND BIAŁOBRZESKIE) USING WATER RETTING [42]

Process	Wax and Fats %	Pectin (%)	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Beniko	0.23	1.47	2.81	71.31	15.03
Wojko	0.24	0.67	3.02	72.53	16.67
Tygra	0.25	0.56	2.78	70.79	15.00
Białobrzeskie	0.34	0.67	2.38	72.03	14.37

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The hemp plant has also been considered a source of essential ingredients and supplements [43]. Hemp fibre contains non-psychoactive and biologically active cannabinoids including cannabidiol. These supplements can be beneficial for anticonvulsant and anxiolytic effects. Hemp seed is an important supplement which contains amino acids, vitamins, minerals, fatty acids, fibres, etc [44], [45]. Consequently, hempseed oil contains healthy polyunsaturated fatty acids. In addition, hemp plant sprouts possess antioxidants [46], [47].

3 Hemp Fibres: Fillers for Composites or Nanocomposites

3.1 Hemp Fibre Treatment

Several physical and chemical techniques have been applied to modify the hemp fibre surface for the formation of high performance composites [48]. Hemp fibre modification resulted in better matrix-fibre interactions with the polymers [49]. These fibres are made up of cellulose and hemicelluloses, and therefore possess polar and hydroxyl groups and a hydrophilic nature [50]. On the other hand, most polymers are hydrophobic. Consequently, non-modified hemp fibres cannot be compatible with polymers to enhance the matrix-fibre adhesion and stress transfer properties [51]. Chemical approaches have been widely studied for modifying hemp fibres [52].

Among these methods, alkali treatments have been commonly applied for the functionalisation of hemp fibres and to develop interactions with polymers [53]. Here, NaOH, KOH, LiOH, etc have been used to remove the hemicellulose, lignin, etc from the fibre surface to enhance the crystallinity and surface properties [54]–[56]. The physical treatments of hemp fibres can be carried out through heating, cold plasma method, electron radiation, UV irradiation, etc [57]–[59]. Biological approaches have also been considered for hemp fibre modification [60]. Accordingly, change in the properties of hemp fibres were observed through bacterial, fungal and enzymatic actions [61]. These methods are environmentally friendly; they are, however, time-consuming when compared to the chemical or physical techniques. Among all methods, physical approaches can be beneficially used owing to facile processing and the least use of toxic chemicals or moisture [62]. Other approaches have been researched in the literature for hemp fibre modification [63].

3.2 Polymers for Hemp Fibres

Thermoplastic and thermosetting polymers have been used as matrices for hemp fibre composites. Among the thermoplastic polymers, polyethylene, polystyrene, polypropylene, poly(lactic acid), etc have been commonly used [64]. Polypropylene with hemp fibres revealed light weight, low price, easy processing, and thermal, tensile and corrosion stability [65]. The major drawback of polypropylene or hemp fibre composites was identified as moisture absorption owing to the hydrophilic nature of these fibres [66]. The moisture uptake was found to decrease the matrix-fibre bonding and overall properties. In this regard, various additives have been used to enhance interfacial bonding of hemp fibres with polymer matrices [67]. Among the thermosets, polyester and epoxy are commonly used with hemp fibres. During the composite formation, the processing temperature need to be controlled (< 100 °C) and must be lower than the degradation temperature of hemp fibres (~ 150 °C) [68]. Sèbe *et al.* [69] reported the polyester or hemp fibre composites using the resin transfer moulding (RTM) technique. These composites had a high impact strength and flexural properties. Other methods used to develop thermoset or hemp composites for high performance applications include vacuum-assisted RTM, pultrusion, and hand lay-up [70]. Despite the advantageous properties of thermoset or hemp composites, their recycling can be challenging to meet the demands of developing ecofriendly and sustainable materials [71].

3.3 Composites of Hemp Fibres

Composites of hemp fibres have been formed through blending with polymers and/or mixing with other fibres [72], [73]. Here, the mechanical properties of natural composites based on hemp fibres have gained attention. Chaudhary *et al.* [15] introduced hemp fibres and jute fibres in the epoxy matrix. The resulting epoxy or hemp fibre composite had a lower tensile strength (58.6 MPa), relative to the epoxy or jute fibre composite. On the other hand, introducing both hemp and jute fibres in the epoxy matrix enhanced flexural strength of the composite up to 86.6 MPa. Maslind *et al.* [74] investigated the influence of water absorption properties of hemp fibres on the tensile or flexural strength of the epoxy composites. When compared to the epoxy or hemp fibre composites, the pristine epoxy matrix with the hemp or kenaf fibre combination revealed enhanced mechanical properties. Stelea *et al.* [75] studied hemp fibres and their composites with recycled polyester and polypropylene matrices. They applied the thermoforming process for the formation of composite materials.

The morphology and the thermal and mechanical properties of hemp fibres and ensuing composites have been explored. Fig. 3 presents a process for the formation of hemp-based composites. The diagram demonstrates steps of the processing of non-woven hemp fabric through needle punching. The non-woven hemp fabrics were overlapped in longitudinal and transversal orders. Afterwards, the thermoforming process was used to press the fibres between the plates along with the polymer to form the composite. The temperature can be maintained at 200 °C and pressure at 700 MPa (10–15 min) depending on the polymer type. Fig. 4 depicts scanning electron microscopy images of hemp fibres, polypropylene, and polyester fibres, and the resulting composites with these fibres. The morphology of polymer fibres was seemingly complicated when compared to the neat hemp fibres. On the other hand, in composite materials, a homogeneous fibre structure with 20–30 μm size was observed. The microstructure of the fibres was therefore found more consistent in the composites, relative to the pristine fibres.

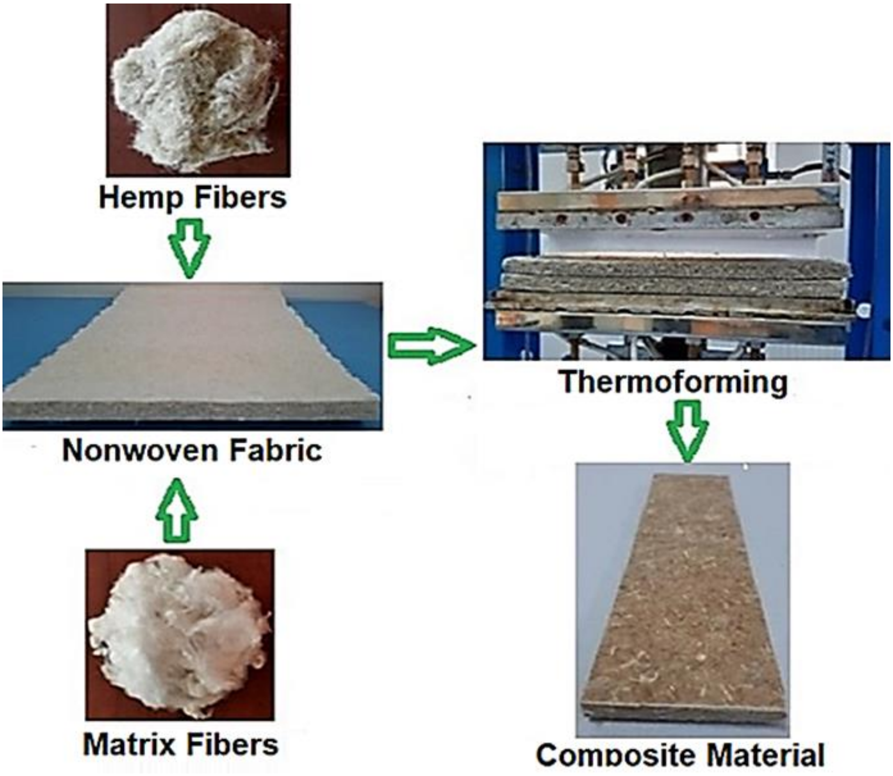

Fig 3. Processing of hemp fibre composites [75].
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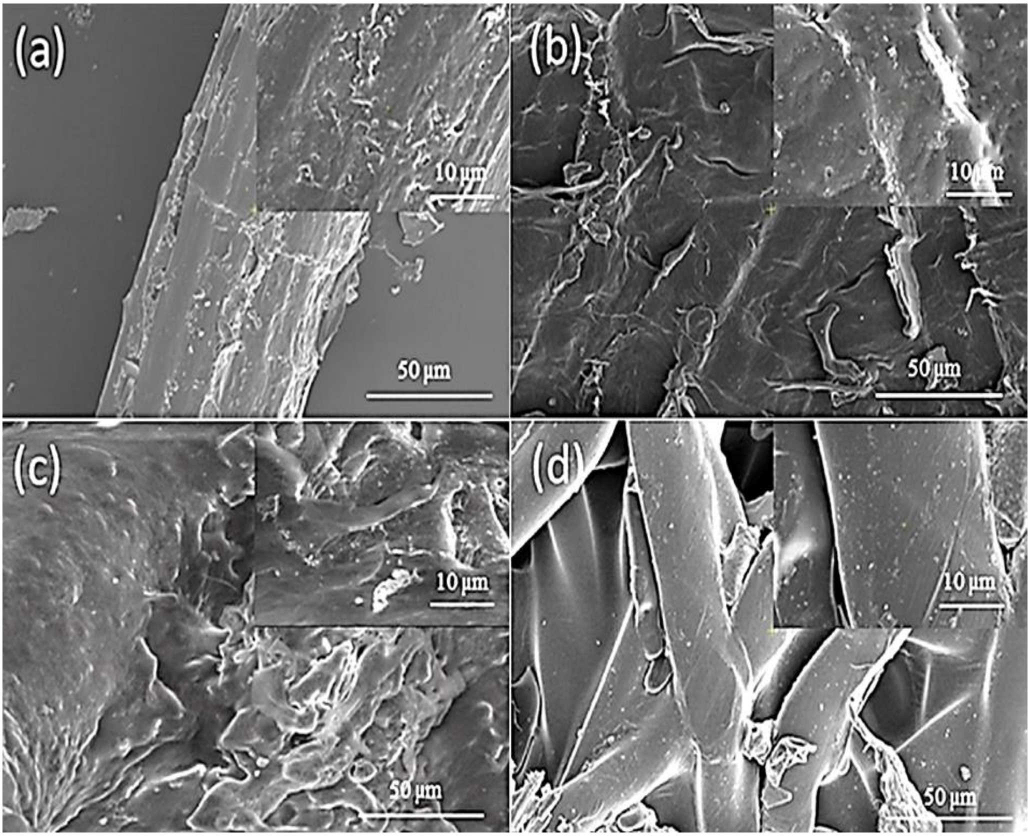

Fig. 4. Scanning electron microscopy images of (a) hemp fibres; (b) polypropylene; (c) polyester; and (d) fibre composite [75].
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Fig. 5 reveals the thermogravimetric curves and differential scanning calorimetric curves for the hemp fibres and polymers. The thermogravimetry analysis showed the initial mass loss of 7% in the range of 100–300 °C due to moisture loss of hemp fibres. The major mass loss of 58% was observed around 300–300 °C owing to cellulose and hemicellulose degradation. The composites revealed a higher degradation temperature due to mutual interactions and formation of a stable structure. In differential scanning calorimetry cooling process, crystallisation peaks of polymers were observed at 112 and 166 °C, while for the composites a higher value of 201 °C was obtained. For hemp fibres, the exothermic heat flow was found constant in the studied temperature range. Similarly, other polymers have been applied as matrices for hemp fibres and resulting properties were scrutinised [76].

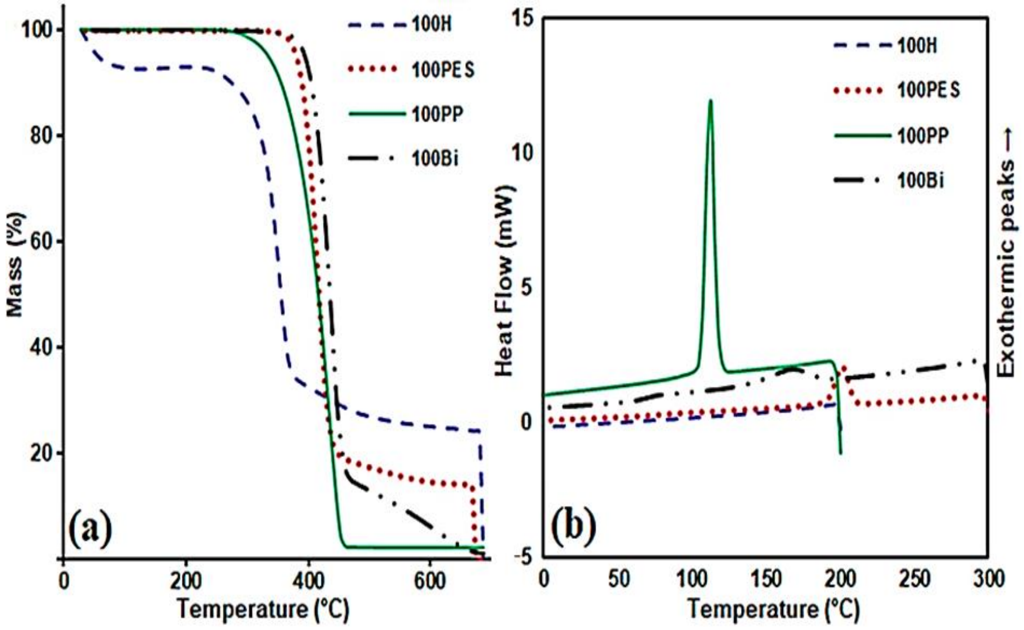

Fig. 5. (a) Thermogravimetric curves. (b) Differential scanning calorimetry cooling curves for hemp fibres and various matrices [75].
H = hemp fibres; PES = polyester; PP = polypropylene; Bi = composite.
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4 Hemp Fibres Derived Nanocomposites

Graphene and graphene oxide have gained an important stance in the nanocarbon nanomaterials [77]. Graphene has a unique one-atom thick nanostructure and various remarkable structural and physical properties such as high surface area, mechanical strength, and electrical conductivity. Graphene oxide is a vital derivative of graphene and has surface functionalities such as hybroxyl, carbonyl, and carboxylic acid. Graphene and graphene oxide have been opted for surface modification of natural fibres [78]. The hemp fibres coated with graphene or graphene oxide have developed fine interfacial bonding with the polymers [79], [80]. The improved mechanical and thermal properties were therefore observed. In addition, graphene oxide has the advantage of biocompatibility for the formation of green nanocomposites. Da Silveira *et al.* [81] investigated the morphology, crystallinity, and thermal properties of graphene oxide coated hemp fibres. Javanshour *et al.* [82] introduced graphene-oxide modified hemp fibres in the epoxy matrix. The resulting epoxy or graphene oxide or hemp fibres have a 2 GPa higher tensile modulus and 43% higher interfacial shear strength than the composites without graphene oxide. Likewise, several other studies have explored the formation of hemp fibre nanocomposites with graphene or graphene oxide [83]. Consequently, inorganic and metal nanoparticles have also been employed for the formation of high performance hemp fibre nanocomposites [84].

5 Applications of Hemp Fibre, Hemp Fibre Composites, and Hemp Fibre Nanocomposites

5.1 Synchrotron X-Rays and Neutrons Scattering Applications

Important studies have been observed regarding the interaction of radiations with the hemp fibres or hemp fibre based composites [85]–[87]. The effect of radiation on hemp-based materials was studied owing to inherent anti-radiation potentials, anti-light or anti-UV features, high heat resistance, thermal insulation, etc [88]. Consequently, hemp fibres have been studied for various irradiation effects including the synchrotron and neutron scattering [89]. Zhang *et al.* [90] studied the hemp fibre coatings used in the instruments for shielding harmful radiations. The hemp materials had fine radiation permeability and heat stability up to 370 °C. Bourmaud *et al.* [91] applied synchrotron X-ray phase-contrast microtomography on the hemp fibre stems. After exposure, the hemp fibres revealed a stretched texture with few kink-bands and pores [92]. Nishiyama *et al.* [93] studied the exposure of synchrotron X-rays and neutrons on the hemp fibre materials. Fig. 6 portrays the synchrotron X-ray diffraction patterns and neutron diffraction patterns studied. The synchrotron and neutrons irradiation were used to detect the formation and changes in the hydrogen bonding, molecular and crystal structure of hemp fibres. It was observed that the hemp sample efficiently diffracted the synchrotron X-rays and neutrons up to 1 Å resolution [94], [95]. The sustainability and biodegradability of hemp materials have further supported the interacting capability of these materials with synchrotron X-rays and neutron radiations [96]–[98]. These valuable hemp fibrous materials certainly need to be further explored for synchrotron X-rays and neutrons scattering applications in future [99].

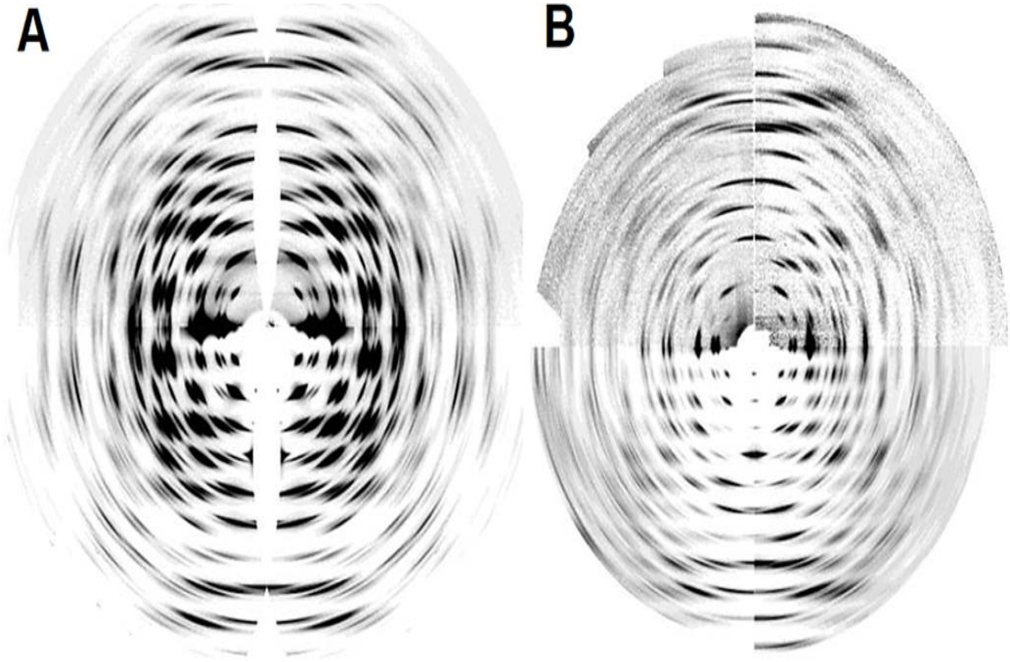

Fig. 6. (A) Synchrotron X-ray diffraction data collected on an online MAR image plate from fibres of Halocynthia. A 3D fit of the Bragg intensities, done using custom-written software that takes into account fibre texture.
(B) Neutron fibre diffraction patterns collected. The 3D fits of the Bragg intensities, done using custom-written software that takes into account fibre texture. The images have been remapped into cylindrical reciprocal space with the fibre axis vertical [93].
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5.2 Water Remediation

Worldwide, the focus has been on waste water treatment owing to rising human health and environmental concerns [100]. The synthetic dyes have been found as major industrial effluents causing ecosystems harms [101], [102]. Dyes are continuously generated from industries such as textiles, paper, food, agriculture and cosmetics [103]. Among commonly used practices for dye removal are coagulation, solvent extraction, adsorption, and chemical oxidation [104]. The sorption methods have been frequently used with carbon and inorganic supports [105]. However, these approaches have been found expensive and uneconomical. For sustainable adsorption of synthetic dyes from waste water, natural fibres have also been considered [83], [106]. In this regard, sustainable sorbents that are based on hemp fibres have been studied with high dye sorption features [107], [108]. The commonly studied dye for sorption properties of hemp fibres is methylene blue dye [109]. Viscusi *et al.* [110] reported hemp fibres for methylene blue dye adsorption from aqueous media. Fig. 7 shows photographs of hemp fibres before and after the dye adsorption process.

Fig. 7. Photographs of fibres before (left) and after (right) dye adsorption [83]. Reproduced with permission from MDPI.

Fig. 8 displays the dye adsorption mechanism at acidic and basic pH. Weak interactions of dyes with fibre surface shows that the dye molecules were protonated (NH+) in acidic conditions, whereas, at basic pH, the basic groups on fibres were strongly bonded to the dye amine functionalities. Fig. 9 shows the dye adsorption on hemp fibres at different temperatures of 25–55 °C. At low concentrations, the intense dye absorption was observed until an equilibrium condition was reached. The dye layer was developed at the interface of fibre absorbent. Hemp fibres therefore offered low-cost, sustainable and ecological materials for water decontamination.

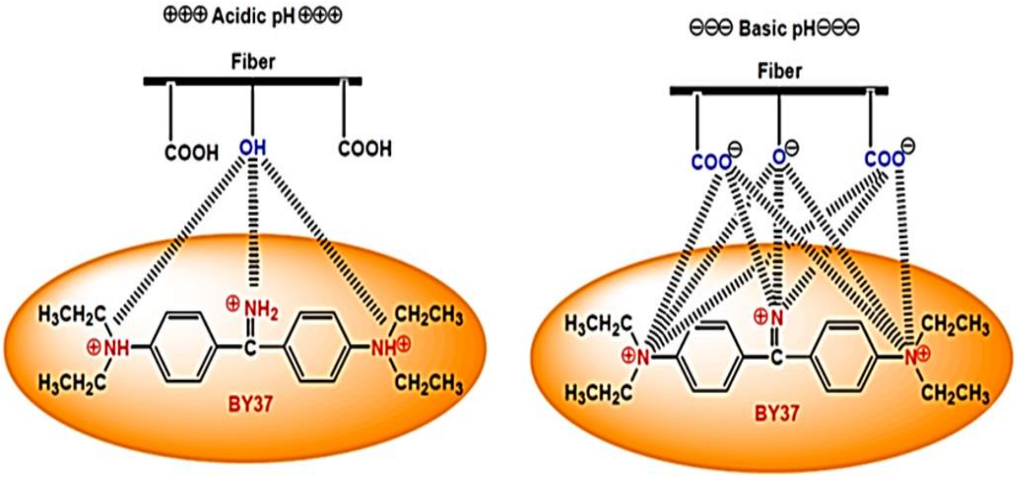

Fig. 8. Proposed adsorption mechanism between the fibre with dye at acidic and basic pH conditions [83].
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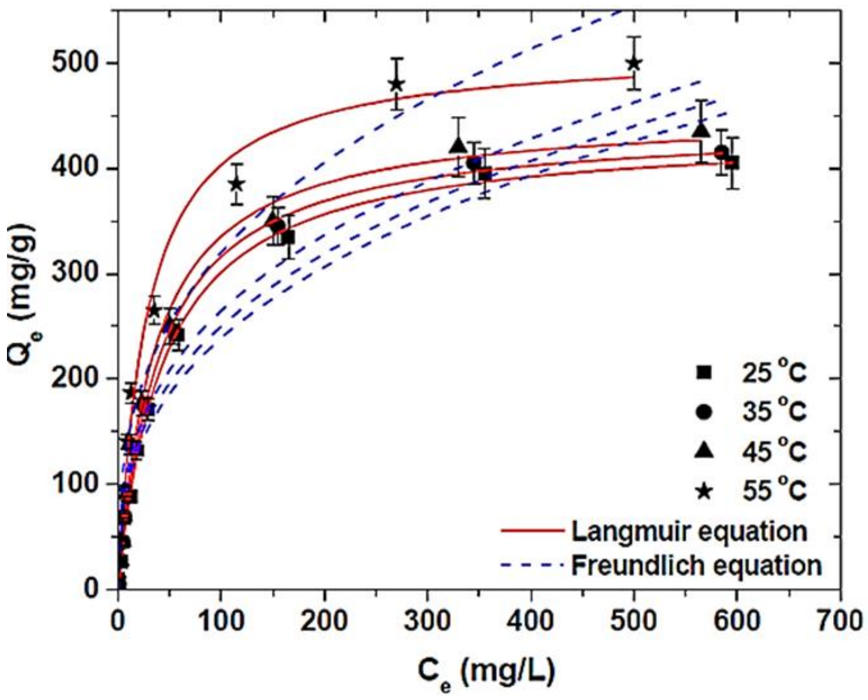

Fig. 9. Isotherms for the dye adsorption at 25, 35, 45 and 55 °C on hemp or flax fibre material [83].
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5.3 Automotive

Industrial hemp fibres have been applied for the automotives and thermal insulation materials [111]. Using eco-polymer and hemp fibres based composites can be the best replacement for auto products [112]. Owing to their high vibration damping capacity, hemp fibres have been applied as fillers in brake pads as substitute for synthetic Kevlar fibres [113], [114]. In addition, these materials have found potential for engine covers, exterior and interior door panels, air filters, sun screens, fuel components, and a range of other automotive parts [115]. However, future research is necessary on these environmentally friendly polymer or hemp fibre materials to improve the durability, thermal and strength properties for vehicles [116].

5.4 Textiles, Food, Construction and Others

In textiles, sustainable and ecofriendly hemp fibres have been found advantageous [23]. The use of hemp fibres can be dated back to the seventh century in the formation of military clothing during the world wars [117]. The hemp fibre based textiles have smoothness, wear resistance, and radiation and bacterial protection features [118]. Hemp fibres have also been used as core food powder for nutritional values of military foods during wars [90]. In addition, hemp fibres have been applied as sustainable construction materials, especially as fibre reinforced concrete [119], [120]. Such materials may reduce the indoors humidity and energy consumption [121]. Hemp concrete also has the capability to better protect the greenhouse gas emissions as compared to the construction materials used [122], [123].

6 Analysis and Conclusions

Advances in the fields of science and technology demand the use of durable, biodegradable, ecofriendly and sustainable materials. Owing to the countless advantages of structural, mechanical, thermal, damping, ecological, sustainability and other properties, the composites and nanocomposites of hemp fibres have been developed and studied. The surface modification of hemp fibres has been found indispensable to develop better compatibility, adhesion and bonding with the polymers. Accordingly, this pioneering review is an effort to report the fundamentals, composites or nanocomposites, and essential applications of the hemp fibres. These applications have been observed for synchrotron X-rays and neutron scattering, water remediation for dye removal, automotives, textiles, building, and many more. However, in-depth future studies are necessary in all these fields for fine tuning the properties and performance of hemp fibres and related materials. This review can therefore be a useful guide for the scientists and researchers seeking advancements and upcoming application areas of these important natural fibres.

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