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(REVIEW ARTICLE)

Industrial *Cannabis sativa* (fiber or hemp): Retting, Hemp Cellulose Extraction and Composite Thin Films for Food Packaging

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Abstract

This literature review paper highlights preparation of hemp cellulose based thin films for the food packaging industries. The Industrial *Cannabis sativa* L. (Hemp) is a short-season crop with many applications which is used as a functional food, fibre, 3D printed building material hempcrete, biochar, bioplastic, paper, textile, biofuel, oil, cosmetics, skincare, animal bedding, ropes, medicine and as a replacement for graphene in supercapacitors. The hemp stalk has two main fibre types: long outer bast fibers and short inner hurd fibres. The outer bast fibres surround the vascular tissue of the hemp stalk. The main macromolecular compound that occurs in bast fibres is cellulose (40 and 80% of dry mass) used for the preparation of composite films for food packaging industries. The extraction of fibers from harvested hemp stems begins with "retting" for an initial weakening of interactions between the fiber bundles and the woody core and surrounding tissue. Cellulose measured at nanoscale is known as nanocellulose. Nanocellulose are of two types which are cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs). Nanocellulose could replace petroleum-based materials due to its promising advantages, including rich sources, biodegradability, excellent mechanical properties, and biocompatibility. Nanocellulose composite films and coatings can extend shelf life and maintain the quality of diverse food products such as fruits, vegetables, and meats, as has already been reported by some relevant studies.

Keywords: Bast Fibers; Cellulose; Composite Films; Food Packaging; Hemp; Hurd Fibres; Nanocellulose; Polylactic Acid (PLA); Retting

1. Introduction

Cannabis sativa L. belongs to the family *Cannabaceae* was used as a medicine before the Christian era in Asia, mainly in India, China, Bhutan, Nepal, Afghanistan, Pakistan, Egypt, Africa, Iran, Persians and Latin America [1-66, 72, 76, 82, 83, 86, 91, 97, 141-152]. The U.S. Farm Bills describe hemp as "*Cannabis sativa L.* and any part of that plant, whether growing or not, with a Λ-9 tetrahydrocannabinol (THC) concentration of not more than 0.3 percent on a dry weight basis [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The Industrial *Cannabis sativa L.* (Hemp) contains very low levels of Λ9-tetrahydrocannabinol (THC) (0 to 0.3% of dry weight) grown outside in a large agriculture farm for the production of fibre, seeds and oil [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Industrial *Cannabis sativa L.* (fiber or Hemp) is legalized by FOOD SAFETY AND STANDARDS AUTHORITY OF INDIA (FSSAI), Government of India, New Delhi since 2021 grown for seed, fibre, medicine, as the functional food, fiber and hempcrete in Uttarakhand state, India [1-43]. The hemp plant will continue to find new applications due to its unique properties for sporting goods, musical instruments, portable and wearable energy storage devices, semiconductors, nanomaterials, active packaging, bio-composite orthotic devices, and medical applications [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Over 500 constituents have been identified in

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hemp—some of the secondary metabolites are cannabinoids, flavonoids, stilbenoids, terpenoids, lignans, and alkaloids, and rapidly growing interest has been seen for the valorization of these metabolites [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. The primary product categories with market potential are fiber, oilseed, and pharmaceuticals [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Applications for hemp can be grouped into traditional, industrial, and emerging (novel) applications [1-43, 141-152]. Hemp and its derivatives have been used for traditional applications, such as baskets, ropes, animal bedding, biomass, clothing, and paper pulp, and in industrial applications, such as building materials, foods, biofuel, oil, cosmetics, skincare products, pharmaceuticals, automotive materials, packaging materials, and sporting goods [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Some emerging applications are its use in supercapacitors, semiconductors, biomaterials, composites, and cellulose nano-fibril bioproducts [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152].

The Industrial *Cannabis sativa L.* (Hemp) is a short-season crop that uses less water, unlike other fiber plants like cotton (hemp requires 2.5 times less water than cotton per unit cultivation area) [1-66]. It adapts well to different climatic types and soil conditions [1-60]. Its cultivation benefits include the absorption of heavy metals and carbon-sequestering properties [1-43, 141-152]. It has also been known to have nutritional benefits and can be cultivated for its seed, fiber, cannabinoid, or flowers [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Its myriad consumer and industrial applications, availability, and short life cycle give hemp a good market value; its products can be economically competitive with alternative materials [1-43]. It has a greater per-hectare yield and lower agricultural costs (70% reduction) as an alternative to cotton in the textile industry [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. It has advantageous material and processing properties, making hemp paper seven times more recyclable than wood pulp paper, and does not require bleaching, reducing relative environmental impacts [1-43, 141-152]. The industrial hemp market has seen rapid growth as the material has been evaluated for a variety of industry applications [1-43,138, 141-152]. A range of applications for hemp has emerged, with over 25,000 hemp or hemp-based products and uses reported in the literature [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Hemp has been applied in filaments for 3D printing, as a harmonic steel cable net replacement, as fiber reinforcement for automotive composite parts, and for the production of carbon nanosheets as a replacement for graphene in supercapacitors [1-66, 138, 141-152]. However, the utilization of hemp has not been fully developed globally due to the knowledge gap in its cultivation and processing and insufficient data across its life cycle. In addition, there has been a shortage of hemp production, a lack of process technology development, market competition with alternative crops, and regulatory risks [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Hemp fibers have high strength, low density, and high sustainability. Therefore, they are used as reinforcement in composite materials. In the following section, the hemp retting, cellulose extraction and production of composite films from hemp for food packaging has been discussed.

2. Hemp Stalk: Bast and Hurd Fibres

The hemp stalk has two main fiber types: long bast fibers and short hurd fibers [1-40]. The outer bast fibers surround the vascular tissue of the hemp stalk, whereas the hurd makes up the woody core [1-43, 82]. Hemp is a bast fibre, which means fibre is extracted from the stalk of the plant [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Conventionally, hemp fibres have been extracted in a long fiber (50–60 cm) form, with a significant quantity of short fibers [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Hemp fibre, as lignocellulosic raw material, shows similarities to other bast fibres due to the comparable chemical composition of this fibre group [1-118]. Fibres extracted from fibrous plant stalks contain cellulose, hemicellulose, lignin, pectin, waxes, fats and ash [1-66]. The bast fibre, as a lignocellulosic material, consists of mainly cellulose, hemicellulose and lignin in its chemical composition [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Hemp fibres, similar to other natural fibres, have several bottlenecks resulting from their nature, the most significant is the lack of homogeneity [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. The lack of repeatability of fiber properties in batches delivered from farmers year by year is an essential disadvantage; the unevenness of fiber linear density, diameter and properties creates difficulties in the detailed design of processing the fibres and the planning of the quality of hemp products [1-43]. Hemp fibers showed a high ability for moisture absorption from surrounding areas, similar to other hydrophilic cellulosic materials [1-40]. The amount of bonded moisture by bast fibers depends on the surrounding air humidity [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152].

Hemp fibers are found in the plants outer stem tissues, referred to as bast fibers [1-66]. This is in comparison to cotton, whose textile is found in the boll or fruit [20-40]. Bast fibers are made of primary and secondary fibers [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. Primary fibers are longer and larger compared to secondary fibers [1-40]. Secondary fibers are shorter and thinner with heavily lignified cell walls [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. These characteristics make the former desirable for textile use rather than the latter [1-66]. Due to their characteristics, secondary fibres are mainly used for cordage, pulp, and recycling additive purposes [1-66]. The presence of secondary fibres decreases along the stem and increases with plant age [1-66]. As bast fibres qualities change with plant age, due to the increasing presence of secondary fibre, plant harvesting time is key to increase fibre extraction quantity [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Hemp offers robust bast fibers, which are divided in primary and secondary fibres [1-40]. The primary fibres are longer and finer, whereas the secondary fibres are shorter and coarser [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152]. For the textile use, only primary fibers can be processed, since the size of the secondary fibres makes it impossible to process and spin them into homogenous yarns [1-40]. These primary fibres are produced during the so-called vegetative growth phase of the plant before flowering [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The flowering generally occurs between 70 to 90 days after sowing, the harvest of the seeds normally happens 4 to 6 weeks later [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. When cultivating fiber crops, the sowing density is higher than for seed crops, as the plants are primarily growing in height and less in width [1-66]. This leads to a higher stem yield, even if not necessarily to a higher bast fibre yield [1-66, 72, 76, 82, 83, 86, 91, 97, 138].

Nevertheless, the secondary fibers are valuable for other end-uses [1-44]. In general, the fibers have a length from 5 to 55 mm and their diameter varies from 16 to 40 µm [1-60]. They are highly moisture absorbent, offer a good breathability and thermal insulation [1-40]. The separation of secondary fibers from primary fibres has not been accomplished effectively during fiber decertification [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. However, the quality variability can be reduced with the use of biological or physiochemical processing allowing for future reliable methods for industrial processing of hemp fiber [1-40]. In general, a high dry matter yield with high primary bast fiber content and low secondary bast fibre is ideal for the extraction of fiber for textile uses [[1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The amount of European hemp fibers used for clothing only amounts to 0.1% [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. When cultivating hemp, no waste arises, since all the parts of the plant can be used for different purposes [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The shivs are a by-product during the separation of the fibre from the core [1-40]. Since the shivs are highly absorbent, the biggest market for them is in the field of animal bedding, having a share of 63 % [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Other application areas are in the use for garden mulch (19 %) and steadily growing in the construction area (16 %), e.g. as hempcrete [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Another profitable market for the farmers of industrial hemp is in the field of hemp seeds and oil [1-66, 72, 76, 82, 83, 86, 91, 97, 138, 141-152].

3. Chemistry of Hemp Fibre

According to the Zimniewska (2022) [83] review, fibers extracted from fibrous fibrous plant stalks contain cellulose, hemicellulose, lignin, pectin, waxes, fats and ash [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The main macromolecular compound that occurs in bast fibres is cellulose in amounts ranging between approximately 40 and 80% of dry mass depending on the fibre type, variety and extraction method [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Cellulose is a polysaccharide and its high chemical reactivity is reached due to three hydroxyl groups –OH, which causes a high propensity for cross-linking during chemical modification. Cellulose is hydrophilic, with a contact angle between 20 and 30 degrees and insoluble in water and most organic solvents [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. According to the Zimniewska (2022) [83] review, a feature of cellulose, the main component of fibre, plays a crucial role in the resulting properties of hemp fiber, determines fiber absorptivity, dyeability, ability for chemical modification as well as suitability for fibre processing [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Hemicellulose is one of a number of heteropolymers (matrix polysaccharides) such as arabinoxylans, present along with cellulose in almost all terrestrial plant cell walls [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Hemicelluloses with cellulose bonded by the cross-linking of cellulose micro fibrils, represent approximately 20% of the plant biomass [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. Hemicellulose dominates the middle lamella of the plant cell and provides middle-ground support for the cellulose on the outer layers of the plant cell. Hemicellulose can also interact with lignin to provide structural tissue support of more vascular plants [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. In bast fibers, pectin glues micro fibrils and elementary fibers together, creating bundles, complexes called technical fibers [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The presence of pectin in technical fibers is unwanted because it creates difficulties in fibre separation and further textile processing [1-66, 72, 76, 82, 83, 86, 91, 97, 138]. The applied process of straw retting results in the reduction of pectin content in the hemp biomass. The bast fiber, as a lignocellulosic material, consists of mainly cellulose, hemicellulose and lignin in its chemical composition [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

The extraction of fibres from harvested hemp stems begins with "**retting**" for an initial weakening of interactions between the fiber bundles and the woody core and surrounding tissue (i.e. initial loosening of the stem structure) [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. That is followed by mechanical processes to separate the fiber bundles. The mechanical processes may be broadly classified into the following three steps [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. 1) Breaking: To break up the woody core (i.e. shives or hurds), which is achieved by crushing plant stems through pairs of fluted rolls. 2) Scutching: To remove the broken pieces of woody core as well as short fibers, which is achieved by passing the broken stems through pairs of rotating blades that strike and beat out the undesired material. 3) Hackling: To parallelize scutched fiber bundles and further remove pieces of woody core and short fibers, which is achieved by pulling the bundles through comb-like structures [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Retting may be achieved by traditional processes (field/dew or water), or through industrial technologies as described below [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

4. Hemp retting

4.1. Field (or dew) Retting

During this process, plants are pulled and hemp plants are cut at harvest, and laid out in oriented piles on the field [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Soil microorganisms populate the resting plants and metabolize their soft tissues, making it easier to separate the fiber bundles. Both fungi and bacteria are active in field retting, and the degradation is reported to proceed in almost in a sequential manner [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The first microorganisms to colonize the harvested mass are found to be fungal species, which are able to breach the cuticular layer with extracellular cutinases as well as by hyphal entry through damaged areas [67, 68, 71, 73, 74, 78-90, 92, 94, 96,98]. That is followed by bacterial species that take advantage of the ingress points into the plant structure, and together with fungal species, metabolize parenchyma cells between fiber bundles with pectinolytic enzymes and hemicellulases [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. At later stages, there is an increase of microbial populations producing cellulolytic enzymes, which are responsible for damage to the cellulosic cell walls of bast fibre bundles observed in prolonged periods of retting [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The fungal species most active in the retting process are found to be from the *Ascomycota* and *Basidiomycota* phyla, and bacterial species from the Proteobacteria [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The advantages of field retting are that the residues may serve to enrich the soil, process costs are low, and problems of malodor are avoided [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

4.2. Stand Retting

Also termed as pre-harvest retting, this is a variant of field retting, where the operating principle is to spray standing crop with a herbicide formulations of glyphosate (N-(phosphonomethyl)-glycine) are commonly employed—which then permeates through the plant via the phloem tissues (translocation) causing death and desiccation of the plants [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Microbial populations are then able to colonize and degrade the plant soft tissues (similar to field retting), and aid in separation of the fiber bundles [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

4.3. Water Retting

Water retting is the process where harvested plants are immersed in natural or artificial water bodies (e.g. streams or tanks respectively) to allow for microbial degradation of plant soft tissues [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The retting is initiated by aerobic bacteria (from the *Bacillus* or *Paenibacillus* genus), and on exhaustion of available air, continued by anaerobic bacteria (from the Clostridium genus). The duration required for adequate retting under water (1–2 weeks) is shorter than on the field (5–6 weeks), the influence of weather and geography is minimized; and variables such as temperature and pH levels can be maintained at optimal levels in artificial water bodies [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. There are challenges with field, stand and water retting in the decision making of when to cease the process and transport the biomass to the next stage of processing [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. It is important to achieve control over the degree of retting, since if the plant material is retted overlong; the cellulose begins to be degraded. In field retting, attempts have been made to define "standard" days that normalize retting durations with respect to average daily temperatures and humidity [67, 68, 71, 73, 74, 78-90,92, 94, 96, 98]. The challenges with field and water retting have prompted investigations on developing industrial processes to produce consistent and good quality fiber bundles [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The aim of such processes is often not limited only to isolating the fiber bundles, but also to divide them into finer strands. This process requires removal of the cementitious material from the middle lamella (i.e. interface between elementary fibers), which is as termed "degumming" [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Enzymatic treatments are applied as the other method. The raw material for enzymatic treatment may be whole stems, bark material stripped from the woody core, or "decorticated" material obtained after a brief retting (field/water) followed by mechanical processes to separate out the woody core [67, 68, 71, 73, 74, 78-90,92, 94, 96, 98]. The natural process of retting in the field and in water occurs through microbial populations utilizing pectinases, hemicellulases and cellulases, and thus in principle, enzymatic formulations should contain the same components [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. In another method, microbial treatment is applied. These treatments involve the inoculation and incubation of microbial cultures on plant material (decorticated material, stripped bark or crushed stems) at optimal pH and temperatures for requisite durations, on plants submersed in liquid tanks or on damp plant material in sealed plastic bags [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Such investigations have been performed both with bacterial cultures (e.g. *Clostridium felsineum, Clostridium acetobutylicum, Geobacillus thermoglucosidasius*) and with fungal cultures (e.g. *Schizophyllum commune, Rhizomucor pusillus, Fusarium lateritium, Epicoccum nigrum*) [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. Chemical treatments offer the advantages of being more rapid and less expensive than enzymatic processes, but often yield more coarse fibers. Examples of complexing agents include EDTA, di-ethylene-triamine-pentaacetic acid, oxalic acid, tetrasodium pyrophosphate and sodium tri-polyphosphate; the alkalis commonly employed are NaOH, KOH or Na_2CO_3; and sodium do-decyl sulfate (SDS) is widely used as detergent. Spraying of urea and EDTA after glyphosate application increases rates in stand retting [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

Physical separations of the pectin from the cellulose are also likely observed by presoaking of the harvested stalks in water. This process has improved pectin removal efficiency, attributed to the plasticization of pectin [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. The processes are envisaged either as stand-alone treatments or as pre-treatments for a subsequent enzymatic or chemical process of retting, but it is to be noted that the wastewater may present the same challenges as those from water retting [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98]. On the other hand, air plasma treatments for delignification, a direct exposure of retted stalks to plasma discharge is found less effective as the process cannot be sufficiently controlled to prevent cellulose from being damaged [67, 68, 71, 73, 74, 78-90, 92, 94, 96, 98].

5. Hemp Cellulose

Cellulose is the most abundant biomass and natural biopolymer on earth [72, 115-138]. It has been gaining increasing attention due to its renewability, biodegradability, and remarkable physical and mechanical properties. Cellulose is a linear polysaccharide consisted of repeating anhydro-D-glucopyranose units joint by β-1,4-glucosidic linkages and has a basic chemical formula of $(C_6H_{10}O_5)$ n [72, 115-138]. This biopolymer accounts for approximately one-third of plant tissues that may be regenerated via photosynthesis [72, 115-138]. Cellulose chains are hierarchically combined together to produce microfibrils [72-138]. This process involves the formation of van der Waals forces as well as intermolecular and intramolecular hydrogen bonds among molecular chains [72- 138]. Every cellulose microfibril is constituted of repeating well-ordered (crystalline) and disordered (amorphous) regions [72-138]. Bundles of cellulose microfibrils are assembled into aggregates (macrofibrils) with combination of lignin and hemicellulose [72-138]. In nature, cellulose fibers function as an important structural element to support plant cell walls and are present in the tissues of algae and the cell membranes of tunicates [72-138]. Cellulose and its derivatives have been applied in various fields to produce diverse products, such as paper, tensile products, packaging, food additives, and biomedical materials for drug delivery and wound dressing [72-138]. They can also be disintegrated into a nanoscale to prepare cellulosic nanomaterials with superior mechanical and surface properties [72-138]. Cellulose does not dissolve in water, but swelling results in significant structural defects [72-138]. The cross-linking approach can increase molecular weight and structural rigidity in mimicking high molecular weight commodity polymers. In addition, cross-linking can link cellulose particles and obtain uniform material, which is beneficial when working with various waste materials such as biomass dust, flour, and small fibers [50- 72-138]. However, coated and chemically treated cellulose is less resistant to water migration effects and does not benefit from increased molecular weight, thus retaining issues with water plasticization and swelling [72-138]. As an alternative, a less-known one-step cross-linking method has emerged in recent years based on citric acid cross-linking [72-138]. For this purpose, glycerol has been applied in combination with citric acid to enhance the degree of cross-linking, thus making materials stiffer [72-138]. Hemp plastic offers a greener alternative to conventional plastics, as it is biodegradable and renewable [72-138].

Cellulose measured at nanoscale is known as nanocellulose [72-138]. Nanocellulose is a biodegradable and renewable biomaterial, which has great potential to be incorporated into bioplastic packaging materials to enhance their physical and functional properties [50- 2-138]. Two types of nanocellulose can be extracted from hemp stalks, which are cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) [45-72-138]. Cellulose nanocrystals (CNCs) can be obtained through sulphuric acid hydrolysis while cellulose nanofibrils (CNFs) are often extracted through TEMPO-mediated oxidation of cellulose fibers [50- 72-138]. Currently, the demand for antimicrobial food packaging is rising in the meat industry [72-138]. N-halamine antimicrobial surface modification added to bioplastic materials has the potential to reduce meat contamination, which benefits both consumers and producers. Nanocellulose is the cellulose extract with a structure at a nanoscale (1-100 nm) [45- 72-138]. It is derived from various types of sources, such as hemp, cotton, wood, bacteria, tunicates, and industrial biomass. Nanocellulose are lightweight, biodegradable, and renewable [72-138]. It is classified into three main groups, including cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC) [50-72-138].

6. Extraction of Hemp Cellulose from inner Hurd

According to the method adopted by Liao (2022) [106], the hemp hurd fibres were ground by using a high-speed grinder [106]. The obtained powder was passed through a metal sieve (mesh size, 1.5 mm) and collected for cellulose extraction, which was conducted according to previous methods with some modifications [106]. Briefly, the powder (50g) was treated by 12% (*w/v*) NaOH using a solid/liquid ratio of 1:15 at 80°C for 3 h with continuous stir at 500 rpm

[106]. The alkaline-treated sample was washed thoroughly by using sterile deionized water for 4-5 times until a neutral pH was achieved [106]. The alkaline treatment was repeated one more time to remove the remaining lignin, hemicellulose, and other impurities. Afterwards, the sample was bleached at 80°C for 4 h with continuous stir in a bleaching solution with a solid/liquid ratio of 1:15 [106]. The bleaching solution was prepared by mixing equal volume of an acetate buffer (54 g NaOH and 150 mL of acetic acid in 2 L of deionized water), 1.7% (*w/v*) $NaClO_2$ solution, and sterile deionized water [106]. The mixture was then washed by sterile deionized water for 4-5 times [106]. The bleaching step was repeated for at least 3 times to obtain the cellulose fibres with a color close to white. Finally, the product was dried at 60°C in an oven overnight [106].

7. Extraction of hemp Cellulose from outer Bast Fibre

Hemp stalk was used as the raw material for cellulose extraction. Hemp stalk was washed, air-dried, manually processed into bast and hurd fibers and then stored at room temperature for further processing. According to the method adopted by Liao (2022) [106], hemp bast fibers (30 g) were cut into small pieces (length, 1.5 cm) and were ground by using a high-speed grinder [106]. The obtained fine powder was treated by 12% (*w/v*) NaOH using a solid/liquid ratio of 1:25 at 80°C for 3 h with continuous stir at 500 rpm [106]. The alkaline-treated sample was washed thoroughly by using sterile deionized water for 4-5 times until a neutral pH was achieved [106]. The alkaline treatment was repeated one more time to remove the remaining lignin, hemicellulose, and impurities [106]. Moreover, the sample was bleached in a bleaching solution with a solid/liquid ratio of 1:20 at 80°C for 3 h with continuous stir [106]. The bleaching solution was prepared by mixing equal volume of an acetate buffer (54 g NaOH and 150 mL of acetic acid in 2 L of deionized water), 1.7% (*w/v*), sodium chlorite ($NaClO_2$) solution, and sterile deionized water [106]. The mixture was washed with sterile deionized water for 4-5 times [106]. The sample was bleached again in a bleaching solution with a solid/liquid ratio of 1:20 at 80°C for 1 h with continuous stir at 200 rpm, followed by washing with deionized water for 4-5 times. The final product was dried at 60°C in an oven overnight [106].

The cellulose content of samples was determined according to a reported method by Liao (2022) [106] with some modifications [106]. Hemp holocellulose collected from the previous procedures was treated with a 17.5% (*w/v*) NaOH solution at room temperature for 5 h with continuous stir at 500 rpm [106]. The obtained cellulose was vacuum-filtrated and washed thoroughly with deionized water for 3 times [106]. The obtained cellulose was oven-dried at 60°C overnight and weighed. The cellulose content was calculated by dividing the obtained cellulose mass by the initial sample mass [106].

Main components in hemp bast fibers and hurd include lignin, cellulose, and hemicellulose. Hemp hurd fibers had 20% cellulose and 17% lignin. Liao (2022) [106] reported that the lignin content was close to the reported result (21%-24%), while the cellulose content was lower than the reported result (40%-48%) [106]. Liao (2022) [106] is also of the opinion that this phenomenon was possibly due to the loss of cellulose caused by the pre-treatment and the differences in growth conditions [106]. After alkaline and bleaching treatments, the cellulose content was increased to 85%, and the levels of hemicellulose and lignin significantly decreased [106]. Thus, most impurities were removed during the extraction process [106]. The bleaching process produced several free radicals, such as hydroxyl free radicals and oxygen-derived free radicals, which could damage the chromophore of lignin [106]. Meanwhile, the alkaline treatment effectively broke down the bonding between cellulose and lignin and solubilized hemicellulose, which promoted the release of cellulose from hemp hurd [106].

Liao (2022) [106] reported that the cellulose content of hemp bast fibers was almost three times higher than that of hemp hurd [106]. In addition, hemp bast fibers showed a lower lignin and hemicellulose content compared with hemp hurd [106]. After alkaline treatment and bleaching treatments, the final product achieved a high cellulose purity (97%), and its lignin and hemicellulose contents were controlled at a low level [106]. Therefore, according to the study conduced by Liao (2022) [106], the hemp bast cellulose has a higher purity than hurd cellulose because hemp bast has a higher cellulose content but lower lignin and hemicellulose content [106]. As a result, cellulose in hemp bast could be more easily released than cellulose in hemp hurd [106].

8. Preparation of Hemp Cellulose Plastic

Hemp fibres were collected and dried in under sunlight conditions. Then fibres were cleaned to remove the dust and impurities [100-104, 114]. Hemp oil, also known as hemp seed oil, acts as a binding agent for hemp plastic mixture. Plasticizer is used to bind the hemp fibers together and give hemp plastic its malleable properties. One common option is polylactic acid (PLA), a bioplastic derived from corn starch [100-104, 114]. Begin by cutting or shredding the hemp fiber into small pieces [100-104, 114]. The size and texture of the fibres will affect the final appearance and texture of hemp plastic [100-104, 114]. Therefore, grind the fibers to produce a powder which is further used for making the hemp plastic [100-104, 114]. In a mixing bowl, combine the shredded hemp fiber powder with hemp oil. Then add a natural plasticizer like glycerin to get greater flexibility in finished hemp plastic product [100-104, 114]. he exact ratios will depend on project and the desired properties of hemp plastic [100-104, 114]. Use a spoon to thoroughly mix the ingredients until a consistent, dough-like texture is achieved. Press the mixture into your chosen mold, making sure it is evenly distributed. A tool is used to shape the hemp plastic as needed [100-104, 114]. Allow hemp plastic to dry and set. The drying time may vary depending on the size and thickness of project. Generally, it may take a day or more for the hemp plastic to fully harden. Once hemp plastic is completely dry and solid, carefully remove it from the mold [100-104, 114].

9. Hemp cellulose Composite Film

Nanocellulose can be utilized as a biodegradable material for use in bioplastics to improve their mechanical and barrier properties [51]. Liao (2022) [106] reported that hemp bast cellulose was selected as the raw material for the synthesis of hemp nanocellulose due to its high cellulose content (97%) and yield (49.6%) [106]. Hemp cellulose nanocrystals (CNCs) were synthesized through sulfuric acid hydrolysis for 30 min [106]. The CNC product had a high colloidal stability in aqueous suspension and had an average diameter of 16 nm and an average length of 244 nm [106]. Hemp cellulose nanofibrils (CNFs) were produced by the TEMPO-mediated oxidation with the addition of 8 mmol of NaClO/g cellulose [106]. The cellulose nanofibrils (CNFs) product had a high dispersity and possessed an average diameter of 24 nm and an average length of 292 nm [106]. Application of hemp nanocellulose in developing biodegradable composite films was demonstrated in different film matrix [106]. Hemp cellulose nanocrystals (CNCs) showed a good compatibility in a PVA film, and the addition of 10% hemp cellulose nanocrystals (CNCs) significantly improved the strength, stiffness, and ultraviolet-blocking effect of PVA film [106]. Likewise, hemp cellulose nanofibrils (CNFs) were miscible with PVA in the composite film [106]. When 10% hemp cellulose nanofibrils (CNFs) were added, the PVA film displayed increased strength, stiffness, and ultraviolet-blocking effect [106]. In addition, hemp cellulose nanofibrils (CNFs), Poly-L-lysine hydrochloride (PLH), and Poly (vinyl alcohol) (PVA) were used to envelop a novel composite film [106]. Liao (2022) [106] reported that the film owned a high transparency, good mechanical performance, UV-blocking effect, and antimicrobial activities against Gram-positive and Gram-negative bacteria [106]. The PVA/CNF/PLH film was biodegradable, sustainable, and had great potential to be used as an antimicrobial packaging to improve food quality and safety [106]. According to Liao (2022) [106] both CNCs and CNFs showed a good compatibility in the Poly (vinyl alcohol) (PVA) film, and the addition of 10% nanocellulose significantly improved the strength, stiffness, and ultraviolet-blocking effect of PVA film [106]. In addition, hemp CNFs, Poly-L-lysine hydrochloride (PLH), and PVA were used to develop a novel composite film[106]. The film owned a high transparency, good mechanical performance, UV-blocking effect, and antimicrobial activities against several bacteria, including *Salmonella enterica* serotype Typhimurium, *Staphylococcus aureus, Escherichia coli*, and *Pseudomonas aeruginosa*. The PVA/CNF/PLH film has great potential to be applied as antimicrobial food packaging [106].

10. Hemp Cellulose Composite Film: Food Packaging

Now a day, petrochemical based non-degradable plastic films like polyethylene, polypropylene and polyolefins are causing serious environmental problems throughout the globe due to their hazardous effects on living organisms [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Most of the plastic waste obtained from the food packaging industry causes adverse effect on our ecology in spite of their diverse advantages like low cost, good tensile strength, good barrier and heat-sealing property [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. The main intention of food packaging material is to sustain the quality of the food products throughout the transportation and storage, as well as also to extend the shelf life of the food products by protecting them from, sunlight, oxygen, moisture, and hazardous microbes [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. In order to achieve such, aspire, packaging films must comply with good physicochemical properties [120-140]. Currently there is a growing demand for consumer’s health concerns, food safety, and ecological problems [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Hence, researchers have been actively involved in developing the eco-friendly films by using biopolymers. Recently for broader application polymer composites are prepared by integrating one of the components from natural or renewable resources like polysaccharides, cellulose from plants, proteins, plant extracts to form biocomposite polymers [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. To fabricate biocomposite films, solution casting was employed as it is very easy and fast technique moreover it does not involve any complicated method and tools [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140].

Cellulose is a linear biopolymer and the most abundant organic material on earth. It is widely presented in higher plants, and can be acquired from marine animals, agricultural residues, industrial waste bacteria, and algae [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Natural cellulose has been widely employed for the application of composite materials owing to its advantages, such as low cost, degradability, and remarkable compatibility after modification [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Nanocellulose is prepared by a series of methods, including chemical and mechanical treatments, as well as enzymatic hydrolysis after extracting cellulose from raw materials, and its diameter does not exceed 100 nm. Compared with ordinary cellulose, nanocellulose presents a variety of features, including a high Young's modulus, high crystallinity, high specific surface area, high tensile strength, and other special traits, suggesting promising prospects for application in the fields of papermaking, biomedicine, materials packaging [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140].

Cellulose is a wide source of raw materials and is the most abundant renewable resource currently. It is a linear polymer material with incomplete crystallization, and is composed of amorphous and crystalline regions [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Cellulose materials can be used in primary and secondary packaging. However, their usability is restricted by their lack of ideal barrier properties (against water, oxygen, and ultraviolet) and antibacterial abilities. To solve this problem, the development of high-performance cellulose-based composite materials has become a hot research topic for many scholars [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Nanocellulose, a type of nanomaterial with high crystallinity, possesses superior properties, including renewability, high Young's modulus, specific surface area, and high tensile strength, and has been reported as an additive in green nanocomposite materials for the food packaging industry [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140]. Nanocellulose is a kind of cellulose-derived natural fiber at the molecular level, and can be obtained from lignocellulosic materials, marine animals, bacteria, and algae through extraction methods. Differences in extraction techniques and sources of cellulose fibers have significant influence on the characteristics of nanocellulose [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-140].

11. Extraction process of Cellulose Nanocrystals (CNCs)

Cellulose nanocrystals (CNCs) is a needle-shaped nanoparticle with a diameter of 10-30 nm and a length up to several hundred nanometers [106]. Cellulose nanocrystals (CNCs) are hydrophilic in nature and often synthesized through the hydrolysis of cellulose fibers by strong inorganic acid to remove amorphous regions but retain highly crystalline regions [106]. Most used acids for the preparation of Cellulose nanocrystals (CNCs) include sulphuric acid, phosphoric acid, and hydrochloric acid[106]. Cellulose nanocrystals (CNCs) obtained through sulphuric acid hydrolysis possess a negatively charged surface due to the presence of sulfate half-ester groups, which plays a key role in stabilizing and dispersing Cellulose nanocrystals (CNCs) in the suspension (CNCs own a high surface area-to-volume ratio, biocompatibility, and excellent mechanical properties [106]. To extract Cellulose nanocrystals (CNCs) from cellulose fibers, a series of treatments are required [106]. The pulp or fiber materials are often pre-treated with bleaching and sodium hydroxide (NaOH) to remove the non-cellulose portions, such as lignin and hemicellulose [106]. After acid hydrolysis of cellulose fibers, several purification procedures, such as centrifugation and dialysis, are used to remove the remaining acids and any impurities [106]. The final Cellulose nanocrystals (CNCs) products are obtained in either a suspension or powder form [106].

According to Liao [106] Cellulose nanocrystals (CNCs) were synthesized from hemp fibers based on a reported method with some modifications [106]. Cellulose fibers were degraded using a 64% (*w/w*) sulfuric acid solution with a solid/liquid ratio of 1:8.75[106]. The acid hydrolysis was conducted with continuous stir at 45°C for different time periods (30, 45, 60, 75, and 90 min) [106]. According to Liao [106], the reaction was stopped by the addition of deionized water (dilution factor, 20) [106]. The hydrolysate was centrifuged at 4,612 xg for 10 min, and the resultant precipitant was collected and rinsed by deionized water [106]. After another centrifugation at 4,612 xg for 30 min, CNC suspension was dialyzed against distilled water for 10 d until a neutral pH was achieved. The final product was stored at 4°C for further use [106]

According to the research work by Bahsaine et al., (2023) [105] hemp raw fibers were subjected to a treatment with sulfuric acid (H_2SO_4, 64 wt%) for one hour at a temperature of 45°C with simultaneous shaking [105]. The hydrolyzed solution was successively washed by distilled water and centrifuge at 10 509×g and 10 °C for 20 min [105]. For 5 days, the suspension was dialyzed against distilled water until a consistent pH of roughly 6–7 was attained [105]. Before being stored in the refrigerator for later use, the obtained suspension was sonicated for 20 min [105]. It is possible to acquire CNC in the form of a white mass [105].

Preparation of bio-nanocomposite films (CS/PVA/CNC): According to the research work by Bahsaine et al., (2023) [105], a solvent casting/evaporation method was performed to develop the CS/PVA/CNC bio-nanocomposite films which contain 60% CS, 40% PVA, and glycerol (40 mg) [105]. To begin with, the dissolution of Polyvinyl alcohol (PVA) (Mw = 61 000 g mol−1) (0.4 g) was performed in water preheated to 90 °C and stirred for continuous 2 h [105]. On the other hand, 0.6 g of chitosan (CS) was dissociated in water acidified with 1% acetic acid and stirred for 3 h to get a homogeneous solution [105]. Then, both solutions were blended by magnetic stirring for 1 hour right after adding an acceptable quantity of glycerol as a plasticizer [105]. Different cellulose nanocrystals (CNCs) suspensions (0–0.5–1–2.5 and 5 wt%) were obtained by adding CNC powder to ultra-pure water then were added to the CS/PVA mixture and vigorously stirred for 30 minutes [105]. The generated blends were then placed in a Petri plate and dried for 48–72 hours at room temperature to allow the water to evaporate, leading to the elaboration of bio-nanocomposite films [105]. The obtained films, namely CS/PVA/CNC-0%, CS/PVA/CNC-0.5%, CS/PVA/CNC-1%, CS/PVA/CNC-2.5%, and CS/PVA/CNC-5%, were conserved for further characterizations [105].

One of the recent research works by Bahsaine et al., (2023) [105] reported the extraction of cellulose nanocrystals (CNCs) from hemp fibers using alkali treatment followed by acid hydrolysis and assess their reinforcing capacity in polyvinyl alcohol (PVA) and chitosan (CS) films [105]. AFM analysis confirmed the existence of elongated, uniquely nanosized CNC fibers [105]. The length of the isolated CNCs was approximately 277.76 ± 61 nm, diameter was 6.38 ± 1.27 nm and its aspect ratio was 44.69 ± 11.08[105]. Bahsaine et al., (2023) [105] reported that the FTIR and SEM analysis indicated the successful removal of non-cellulosic compounds [105]. Furthermore, the study of Bahsaine et al., (2023) [105] explored the impact of adding CNCs at varying weight percentages (0, 0.5, 1, 2.5, and 5 wt%) as a strengthening agent on the chemical composition, structure, tensile characteristics, transparency, and water solubility of the bionanocomposite films [105]. Adding CNCs to the CS/PVA film, up to 5 wt%, resulted in an improvement in both the Young's modulus and tensile strength of the bio-nanocomposite film, which are measured at (412.46 ± 10.49 MPa) and (18.60 ± 3.42 MPa), respectively, in contrast to the control films with values of (202.32 ± 22.50 MPa) and (13.72 ± 2.61 MPa), respectively [105]. The scanning electron microscopy (SEM) images revealed the creation of a CS/PVA/CNC film that appears smooth, with no signs of clumping or clustering [105]. The blending and introduction of CNCs have yielded transparent and biodegradable CS/PVA films [105]. This incorporation has led to a reduction in the gas transmission rate (from 7.013 to 4.159 cm^3 (m^2 day\$0.1 MPa)−1, a decrease in transparency (from 90.23% to 82.47%), and a lowered water solubility (from 48% to 33%) [105]. This study by Bahsaine et al., (2023) [105] proposed the utilization of hemp-derived CNC as a strengthening component in the development of mechanically robust and transparent CS/PVA-CNC bio-nanocomposite films, holding substantial potential for application in the field of food packaging [105]. Bio-nanocomposite were developed using a blend of PVA, chitosan, and cellulose nanocrystals extracted from hemp [105]. The inclusion of CNCs up to 5% improved the mechanical properties, maintained transparency, and reduced gas transmission rate [105]. Throughout the course of this research by Bahsaine et al., (2023) [105] non-polluting bio-nanocomposites films based on polyvinyl alcohol (PVA) and chitosan (CS) blend strengthened with cellulose nanocrystals (CNCs) have been developed [105].

Very recently one of the studies conducted by Dash et al., (2024) [137] reported a novel, cost-effective, and environmentally friendly food packaging film or coating using agricultural waste materials such as deccan hemp seeds and leaves [137]. The process involved blending deccan hemp seed protein and leaf extract at an optimal ratio through a casting technique [137]. Additionally, starch isolated from taro root was added into the protein-based film to enhance its structural, barrier, and mechanical properties [137]. The introduction of bioactive compounds, like deccan hemp leaf extract, led to increase in antioxidant activity and enriching the film with beneficial phenolic compounds [137].

Dash et al., (2024) [137] are of the opinion that the combination of leaf extract and starch with the protein film resulted in a homogeneous, dense, and smooth film matrix, as evidenced by scanning microscopy images [137]. FTIR spectroscopy confirmed inter-linkage among the various constituents in the film [137]. Rheological analysis of the film-forming solution showed its shear-thinning behavior, with the storage modulus exceeding the loss modulus in the angular frequency range of 0.1 rad/s to 100 rad/s, indicating the film's elastic nature [137]. Furthermore, the physical and optical attributes of the films were enhanced through the addition of starch and leaf extract [137]. Dash et al., (2024) [137] reported that, in a practical application, the film-forming solution was applied to grapes, leading to improved quality and extended shelf life for grapes stored under ambient conditions for ten days [137]. Overall, Dash et al., (2024) [137] study's findings suggested that the use of deccan hemp seed protein-based packaging film holds promise as an emerging solution for enhancing the shelf life of vegetables and fruits, offering a sustainable and effective alternative for food packaging [137].

In one of the study reported by Zhang et al., (2020) [135], UV-shielding and transparency were achieved in flexible hemp/PVA films through the use of lignocellulose from hemp hurd [135]. Lignocellulose particles were prepared through a wet ball milling method without chemical treatments [135]. To understand the limitations of particle size, the relation between milling time and particle size was studied [135]. The smallest size of particles was around 1 μm and crystallinity of the particles reduced after 20 h wet ball milling [135]. Zhang et al., (2020) [135] reported that SEM image shows the homogenized distribution of the micro-particles in the film with low additive amounts [135]. While all fabricated films were highly flexible, the 1 wt. % and 5 wt. % hemp/PVA composite films showed a significant increase

($p \leq 0.05$) in Young's modulus and nominal maximum stress, which were considerably higher than pure PVA film [135]. The hydrogen bond between hemp and PVA and an increase in the crystallinity of film, maybe the reason for enhanced Young's modulus and higher nominal maximum stress of the film [135]. Zhang et al., (2020) [135] are of the opinion that the decrease in Young's modulus and in nominal maximum stress of the 10 wt. % hemp/PVA film were caused by the hemp particle aggregation, as confirmed by SEM [135]. Zhang et al., (2020) [135] reported that compared to a previously fabricated TiO_2/PVA film, the hemp/PVA composite films showed better UV shielding properties performance in the UVA-I range which is a critical range damaging human skin cell [135]. The highest UV-shielding ability of the film was achieved with 10 wt. % hemp [135]. The FTIR results also proved the existing of –C=O groups in quinone or p-quinone of lignin that were persevered by ball milling method [135]. The 5 wt. % film exhibits a good balance between mechanical properties and UV-shielding properties with highly transparent optical properties [135]. The water vapor permeability (WVP) of the composite films showed higher WVP compared to the pure PVA film and comparable with the commercial packaging plastic film made of HDPE (High-density polyethylene) [135]. This work of Zhang et al., (2020) [135] provides additional value to agriculture hemp waste enabling it used as UV-shielding additive [135].

Traditional petroleum-based packaging materials can no longer meet the needs of sustainable development [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-138]. Nanocellulose could replace petroleum-based materials due to its promising advantages, including rich sources, biodegradability, excellent mechanical properties, and biocompatibility [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-138]. Different types of nanocellulose (CNCs, CNFs, and BNC) can be extracted from different sources to obtain desirable characteristics for the preservation of specific products. The techniques to formulate nanocellulose composite films include solution casting, layer-by-layer assembly, electrospinning, melt processing, and coating, which bring about different properties [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-138].

Nanocellulose is often used as a reinforcing agent in other film substrates to enhance barrier properties, UV shielding abilities, thermal stabilities, mechanical, biodegradable, and edible properties in the food industry, demonstrating its great potential for application in the food packaging industry [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-138]. Nanocellulose composite films and coatings can extend shelf life and maintain the quality of diverse food products such as fruits, vegetables, and meats, as has already been reported by some relevant studies. However, it is still hard to transfer these from the laboratory to the market, and the outlook on the preparation and application of nanocellulose composite films has many practical challenges [69-71, 75-77, 82, 91, 93, 95, 99, 104-113, 116-120-138].

12. Conclusion

Hemp is grown primarily for the production of bast fibre that can be made into breathable, durable, and comfortable textiles. The production of hemp fiber includes 4 stages which are retting, decortication, softening, combing and spinning. The hemp is cut and left for 10-20 days to ret. After retting, the hemp stalk is fed into a decortication machine and the hemp fiber is collected for further treatment. Hemp fiber constitutes only 30% of hemp stalk, and rest of the stalk (70%), is mainly hemp hurd. With the huge production of hemp fiber, the large amount of hemp hurd remains as a low-cost by-product. The major components of hemp hurd are cellulose, hemicellulose, and lignin. Cellulose is the primary cell wall of most of the lignocellulosic biomass. It is a linear homopolymer consist of about 3000 to 5000 of β (1→4), D-glucose units linked with glycosidic bonds. Hemp hurd contains around 40–48% of cellulose which makes it an ideal candidate for use in the composite. Currently, single-used plastics including food packaging film is causing severe white pollution. Designing sustainable food packaging film with UV-shielding property can keep the food fresh with a low environmental burden. Hemp hurd, the industrial waste which is rich in lignin and its UV-protective functional groups, has received little attention in this regard.

The extensive utilization of plastic packaging materials derived from petroleum is cost-effective and possesses favorable mechanical strength, high barrier capabilities, and heat-sealing properties. However, despite these advantages, the non-biodegradable and non-renewable nature of plastic undermines its positive attributes. This becomes particularly problematic in the current context, where the use of plastic materials contributes to environmental pollution. In recent times, there is growing concern about the food safety of packaging materials due to the increasing consumption of pre-cut fruits and ready-to-eat food by a significant portion of the population. Consequently, it is essential to embrace sustainable active food packaging as a solution to reduce waste and environmental impact, focusing on eco-friendly materials and techniques. The use of these materials in conjunction with food products not only enhances food safety, quality, and shelf-life but also addresses environmental issues. A key component in the realm of sustainable active packaging is edible packaging, which utilizes biodegradable substances that can be consumed along with the food. This has sparked increased awareness and research efforts in both industry and academia to develop sustainable, edible, and environmentally friendly materials. Additionally, research has intensified in the production of edible films and coatings to extend shelf life of food, incorporating proteins (such as gelatin, cereal proteins, whey protein, and seed protein), polysaccharides (including starch, cellulose derivatives, chitosan, and gums), and lipids (such as carnauba, beeswax, and fatty acids).

Owing to the environmental pollution caused by petroleum-based packaging materials, there is an imminent need to develop novel food packaging materials. Nanocellulose, which is a one-dimensional structure, has excellent physical and chemical properties, such as renewability, degradability, sound mechanical properties, and good biocompatibility, indicating promising applications in modern industry, particularly in food packaging. Meanwhile, the performances of nanocellulose composite films in improving the mechanical, barrier (oxygen, water vapor, ultraviolet) and thermal properties of food packaging materials and the development of biodegradable or edible packaging materials in the food industry are elaborated.

Cellulose nanocrystals (CNCs) fabricated from hemp cellulose was used as a function filler and its compatibility with PVA polymer has been reported. PVA was chosen as the matrix as it is biodegradable, transparent, and able to form film. Hemp hurd is a waste generated by the production of hemp fibre, though contains effective UV-shielding groups from its lignin. Hemp fiber is breathable, resilient, durable and non-allergic which lead to its extensive use, while the hemp hurd remains as a leftover. This natural UV functional groups in hemp hurd could be used as a filler in food packaging film. Sustainable food packaging film with UV-shielding property is in urgent need to ease the environmental pollution from non-degradable plastics and keep the food fresher. The preparation method should be optimized to reduce the cost when nanocellulose is incorporated with other polymers to provide theoretical guidance for large-scale production. Further efforts should be made to find a key addition ratio when combining nanocellulose with other materials to obtain high-performance composite films. Edible nanocellulose composite films as the inner packaging of preserved fruit, pastries, instant soups, and other convenience foods could be developed. Therefore, a comprehensive evaluation of the safety (migration, biotoxicity, ecotoxicity) of nanocellulose composite films should be conducted before large-scale commercial application.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed. This paper is the review of literature.

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