Antibacterial Properties of Hemp and Other Natural Fibre Plants: A Review

Belas Ahmed Khan,[a] Philip Warner,[b] and Hao Wang [a,]*

Intervention against pathogenic bacteria using natural plant material has a long history. Plant materials also have been widely used as fillers and/or reinforcers in polymer composites. Some natural fibre plants, such as hemp, are regarded to possess antibacterial activity against a wide range of pathogenic bacteria. Innovative applications can be explored if they are incorporated in polymer composites. This review aims to compile the relevant investigations on antibacterial activity of hemp and other fibre plants such as jute, flax, kenaf, sisal, and bamboo. The antibacterial character might be contributed from cannabinoids, alkaloids, other bioactive compounds, or phenolic compounds of lignin. This review is intended to encourage utilization of hemp and other natural fibre plants in value-added diversified products. Some potential applications are also discussed.

Keywords: Hemp; Natural fibre; Antibacterial activity; Cannabinoids; Composites

*Contact information: a: Centre of Excellence in Engineered Fibre Composite, University of Southern Queensland, Toowoomba, QLD-4350, Australia; b: Ecofibre Industries Operations Pty Ltd, Jerrys Plains, NSW 2330, Australia; *Corresponding author: hao.wang@usq.edu.au*

INTRODUCTION

Plants are a great source of natural fibres that can be classified as primary fibre plants or secondary fibre plants, depending on their utilization. Cotton, jute, hemp, flax and kenaf are some examples of primary fibre plants that are grown for their high fibre content, while pineapple, oil palm, and coir are secondary fibre plants where the fibres are produced as a by-product (Faruk *et al.* 2012). Natural fibre plants have been used in textiles, composites, and many other sectors (Kalia *et al*. 2009).

The use of plants in medications has a long history, and it was usually the only method available in previous eras (Redo *et al.* 1989). Interest in plants having antibacterial properties has been revived for many reasons, such as the public becoming increasingly aware of problems with the over-prescription and misuse of synthetic antibiotics (Cowan 1999). Antibacterial activity of plant materials is applicable not only in medications but also in various commodities, for example packaging and cosmetics that are used in our everyday life. Antibacterial activity of natural fibre plants can generate more opportunities for innovations. Historically, after fibre extraction from primary fibre plants, the rest of the plant material has had very limited use. However, antibacterial investigations of natural fibre plants may provide improved utilization of these by-products as well.

Hemp is a typical fibre-generating plant with well-known antibacterial performance (Appendino *et al.* 2008; Lone and Lone 2012). Certain other natural fibre plants also show similar properties (Afrin *et al.* 2012; Farah *et al.* 2006; Ilhan *et al.* 2007; Santos *et al*. 2009; Zakaria *et al.* 2011). However, hemp is more highly regarded as a potential medicinal plant and has received more attention than other fibre plants (Benet 1975).

To more fully understand the implications of research that has been done on the antibacterial properties, this review includes different aspects such as the identities and concentrations of active components, the antibacterial activity of extracts, and possible applications. Such observations can provide a basis for the future inclusion of natural fibre plants in composites as antibacterial agents. The main objective of this review is to encourage utilization of hemp and other natural fibre plants in value-added diversified products based on their antibacterial performance.

BACTERIA AND ANTIBACTERIAL METHODS

Before beginning a discussion on the antibacterial activity of natural fibre plants, it would be useful to give some introductory information on pathogenic bacteria and the intervention methods currently being practiced. Pathogens can be defined as those microorganisms that may cause illness in humans, transmitted via air, water, food, or other vectors. A wide range of enteric pathogens and their toxins that can be transmitted via food include the bacteria (such as *Campylobacter* species, *Salmonella* spp., *Shigella* spp., *Escherichia coli*, *Clostridium botulinum*, *Listeria monocytogenes*, *Clostridium perfringens*, *Bacillus* spp., *Staphylococcus aureus*, *Cryptospordium parvum*, *Cyclospora cyatenenesis*, and *Giardia* spp.) and viruses (such as Norwalk-like viruses and Hepatitis A) (Commission 2002). Of the four pathogen types (*i.e.*, bacteria, fungi, parasites, and viruses), it was found that over 90 percent of confirmed foodborne human illness cases and deaths reported to the Centers for Disease Control and Prevention (CDC) are attributable to bacteria (Bean and Griffin 1990; Bean *et al.* 1990).

Various intervention methods are in use to control bacteria. Inactivation of bacteria can be achieved by chemical and/or physical means, such as heat, chemical solutions, gases, and radiation (Curtis 2008; Laroussi and Leipold 2004; Parish *et al.* 2003). Preservative agents are used to ensure that foods remain safe and unspoiled. Weak organic acids, hydrogen peroxide, and chelators are the examples of chemical preservative agents. Naturally occurring preservatives such as small organic antimicrobial biomolecules (for example, benzoic acid, vanillic acid, benzaldehyde, ferulic acid, estragole, guaiacol, and eugenol), antimicrobial proteins and peptides, and cell wall perturbing biomolecules are used as well (Brul and Coote 1999).

ANTIBACTERIAL PROPERTY OF NATURAL FIBRE PLANTS

Plants contain numerous biologically active compounds, many of which have been shown to have antibacterial properties (Cowan 1999; Redo *et al.* 1989). Researchers from divergent fields in the world have investigated plants with an eye to their antibacterial usefulness. Useful antimicrobial phytochemicals identified in the plants can be divided into several categories such as phenolics and polyphenols, terpenoids and essential oils, cannabinoids, alkaloids, lectins and polypeptides, and polyacetylenes. Phenolics and polyphenols include simple phenols and phenolic acids, quinones, flavones, flavonoids, flavonols, tannins, and coumarins (Appendino *et al.* 2008; Cowan 1999; Lone and Lone 2012). Much of the information about the antibacterial activities of plants is anecdotal, although some of them have been scientifically investigated. The antimicrobial properties of the constituents from a wide variety of plants have been reviewed (Cowan 1999; Dixon 2001; Dorman and Deans 2000). Some of the fibre plants, especially hemp, demonstrated potentially important antibacterial properties.

Hemp

Hemp has a long history of cultivation for various purposes including fibre, medicine, recreational drugs, and food (Marks *et al.* 2009). Hemp varieties can be divided into fibre type, intermediate type, and drug type (known as marijuana) with the Δ^9-trans-tetrahydrocannabinol (Δ^9-THC) content ranging from <0.3%, 0.3 to 1.0%, and 1 to 20%, respectively (Ahmed *et al.* 2008; Grotenhermen and Russo 2002).

Bioactive constituents

Hemp contains many classes of chemical constituents (Turner *et al*. 1980), with compounds constantly being discovered and reported. These include cannabinoids, nitrogenous compounds, amino acids, proteins, glycoproteins, enzymes, sugars, hydrocarbons, simple alcohols, simple aldehydes, simple ketones, simple acids, fatty acids, simple esters, lactones, steroids, terpenes, non-cannabinoid phenols, flavanoid glycosides, vitamins, and pigments. The total number of natural compounds identified in hemp is greater than 500 (ElSohly and Slade 2005; Radwan *et al.* 2008). Complex macro-composition of hemp and numerous compounds within the plant have the potential to exhibit antibacterial activity.

Cannabinoids are the typical group of C21 compounds present in hemp, and they are in the form of carboxylic acids, analogs, and transformation products (Mechoulam and Gaoni 1967; Razdan 1986). The compounds are either structurally or pharmacologically similar to Δ^9-THC or those that bind to the cannabinoid receptors. The 86 known cannabinoids (Ahmed *et al.* 2008; ElSohly and Slade 2005; Radwan *et al*. 2008a,b) from hemp plant can be classified into 11 structural types: cannabigerol (CBG), cannabichromene (CBC), cannabidiol (CBD), Δ^9-THC, Δ^8-THC, cannabicyclol (CBL), cannabielsoin (CBE), cannabinol (CBN), cannabinodiol (CBND), cannabitriol (CBT), and miscellaneous types. In hemp, the most prevalent cannabinoids are Δ^9-THC, CBD, and CBN, followed by CBG, CBC, and CBND. The others are minor. Some cannabinoids extracted from hemp were found to show excellent antibacterial activity (Appendino *et al.* 2008; Lone and Lone 2012; Radwan *et al.* 2009).

There are three sources of cannabinoids. Plant-derived cannabinoids sometimes termed phytocannabinoids (Lambert and Fowler 2005) such as Δ^9-THC and CBD, occur uniquely in the hemp plant. Endogenous cannabinoids, also known as endocannabinoids (such as anandamide and 2-arachidonoylglycerol), are produced in the bodies of humans and animals. Synthetic cannabinoids, such as WIN-55, 212-2, JWH-133, and (R)-methanandamide (MET), have been developed in the laboratory with structures similar to plant or endogenous cannabinoids (Sarfaraz *et al.* 2008).

Active components in different parts of hemp

The concentrations of bioactive compounds in hemp depend on tissue type, age, variety, growth conditions (nutrition, humidity and light levels), harvest time, and storage conditions (Hirofumi *et al.* 1980; Keller *et al.* 2001; Ross and El Sohly 1996). For example, the hemp grown in northern latitudes is reported to have a high content of CBD and Δ^9-THC, resulting in strong antimicrobial activity (Leizer *et al.* 2000). Cannabinoids are found in all parts of the hemp plant, but the most potent resinous exudate comes from the flowering tops. The potency of the clinical effects of cannabinoids is determined by the type of seed and the part of the plant being used but not by the climate or soil, as had once been assumed (Walsh *et al.* 2003). Fairbairn and Liebmann (1974) reported that a cool climate and poor lighting conditions do not seem to prevent the production of active components *i.e*. THC and CBD. It has been found that the concentration of THC varies between and within individual plants (Fairbairn and Liebmann 1974; Latta and Eaton 1975). Seasonal fluctuation in cannabinoids has been related to stage of development of the plant (Latta and Eaton 1975). Cannabinoids were lowest in seedlings, highest prior to flowering, and at an intermediate level thereafter until physiological maturity. It was also noticed that cannabinoids were highest in flowers and progressively lower in leaves, petioles, stems, seeds, and roots; however, cannabinoids content of male and female flowers was not significantly different (Latta and Eaton 1975). Most of the investigations on cannabis concentration of hemp plants excludes the roots, stems, and seeds as their cannabinoid content are low (Field and Arndt 1980). Table 1 shows the concentration of bioactive components in hemp in descending order by different parts and by the growing stage of the plant.

Table 1. Concentration of Active Components within the Plant

Different parts of the plant	Growing stage
Flowers	Prior to flowering
Youngest leaves of uppermost nodes	From flowering to physiological maturity
Older leaves along the axis	Seedlings
Petioles	
Stems/hurd	
Outside of the Seeds	
Seed coat and kernel	
Roots	

Hemphill *et al.* (1980) reported that cannabinoid content varied quantitatively and qualitatively in different organs of hemp plants of different geographical origins. Leaves of different ages were analysed, and it was revealed that the youngest leaves from the uppermost nodes of the flowering plants of fibre type strains contained the highest level of their characteristic cannabinoid. The concentrations of cannabinoids in fibre type hemp plants decreases progressively along the axis, with the lowest level of cannabinoids present in the mature and old senescing leaves. Again, bracts of fibre type plants possess high level of CBD and low level of Δ^9-THC, while bracts from the drug type plants contained high levels of Δ^9-THC with low concentrations of CBD or CBC.

Analysis of hemp seeds of both drug type and fibre type for their Δ^9-THC concentration has been carried out by Ross *et al.* (2000). It was noticed that cleanliness of the seeds plays a major role in the apparent concentration of Δ^9-THC in hemp seeds. Investigation also suggested that the bulk of Δ^9-THC in the hemp seeds resides on the outside of the seeds, with only small amounts in the seed coat or the kernel itself (Ross *et al.* 2000). Thus the content of THC in hemp oil can come only as a result of the technical process of harvesting the fruits (Mölleken and Husmann 1997).

Antibacterial performance

Extraction, which separates bioactive compounds of the plant tissues from the inactive/inert components, is the most frequently used method to evaluate antibacterial effect of plant materials. Common solvents used for active component extraction are water, ethanol, methanol, chloroform, dichloromethanol, ether, and acetone (Cowan 1999; Ncube *et al.* 2008). Solvents used in the extraction methods have great influence on the amount of active compounds that can be extracted and thus the result of the antibacterial performance of a plant.

Hemp extracts using organic solvents exhibited very good antimicrobial activity against *S. aureus*, as reported by Borchardt *et al.* (2008). Cannabinoids extracted from the hemp leaves by aqueous produced a total yield of 3.8 g, while an acetone extract produced a total of 4.8 g (Lone and Lone 2012). *In vitro* antimicrobial studies were conducted with aqueous, ethanolic, and petroleum ether extracts of the hemp leaves (Wasim *et al.* 1995). The acidic fraction was obtained from the ethanolic extract and 2% sodium hydroxide extract. The ethanolic extract, petroleum ether extract, and the acidic fraction exhibited activity both against Gram-positive and Gram-negative bacteria and also against the fungi used in the study. However, the aqueous extract did not show any antimicrobial activity.

Apart from the extraction method, several other factors also influence the results of antibacterial investigations, such as the environmental and climatic conditions under which the plant grew, choice of plant extracts, antibacterial test method, and the test microorganisms used (Nostro *et al.* 2000).

Researchers have reported antibacterial activity of cannabinoids against a wide range of bacteria (Appendino *et al.* 2008; Lone and Lone 2012; Radwan *et al.* 2009). Appendino *et al.* (2008) extracted all five major cannabinoids from hemp: CBD, CBC, CBG, Δ^9-THC, and CBN, and observed their antibacterial activity. It was found that all of them showed potent activity against a variety of *methicillin-resistant Staphylococcus aureus (MRSA)* strains of current clinical relevance. Lone and Lone (2012) extracted cannabinoids by aqueous and acetone and tested their antibacterial performance. The acetone extract exhibited higher antimicrobial activity than that of the crude aqueous extract against the bacteria *Pseudomonas aeruginosa* and *Vibro cholera*, and the fungi *Cryptococcus neoformans* and *Candida albicans*.

The cannabinoids extracts also demonstrated antioxidant activity by changing to yellow colour. Radwan *et al.* (2009) isolated nine new cannabinoids from a high-potency variety of hemp. Three of these displayed significant antibacterial and antifungal activities, while others displayed strong antileishmanial activity. Crude alkaloid from the leaves of hemp plants was extracted, and its *in vitro* antibacterial activities were evaluated against various bacterial strains of microflora and a β-strain of *E. coli* (Das 2012). The study revealed growth inhibition and effectiveness in the extracts of hemp, which suggests that leaves potentially possess a broad spectrum antibacterial activity. Considering the above findings, it is certain that all five major cannabinoids: CBD, CBC, CBG, Δ^9-THC, and CBN, and crude alkaloids from hemp are potential candidates to be considered as natural antibacterial agents. Table 2 summarizes antibacterial activity found in hemp extracts.

Table 2. Antibacterial Activity of Hemp Extracts

Extracts	Activity	Reference
Five major cannabinoids (CBD, CBC, CBG, Δ9-THC, and CBN)	Potent activity against a variety of methicillin-resistant *S. aureus* (MRSA) strains	Appendino *et al.*(2008)
Cannabinoids (crude aqueous acetone extract of leaves)	Inhibition against bacteria *P. aeruginosa*, *V. cholerae* and fungi *C. neoformans, C. albicans*.	Lone and Lone (2012)
(±)-3''-hydroxy-$\Delta^{(4'',5'')}$-CBC, 4-acetoxy-2-geranyl-5-hydroxy-3-n-pentylphenol and 8-hydroxycannabinolic acid	Good anti-*S. aureus* activity, antifungal activity against *C. albicans*	Radwan *et al.* (2009)
Crude alkaloid	Mouth, skin, ear microflora and *β-strain of E. coli*	Das (2012)
Seed oil	Pronounced activity against *B. subtilis* and *S. aureus*, moderate activity against *E. coli* and high activity against *P. aeruginosa*	Ali *et al.* (2012)
	Inhibit the growth of *A. niger*, *E. coli*, *S. aureus*, *S. cerevisiae*, and *P. aeruginosa*	Leizer *et al.* (2000)
Petroleum ether and Methanol extract of the whole plant	Pronounced antibacterial activity against *B. subtilis* and *S. aureus*, high activity against *E. coli*	Ali *et al.* (2012)
Ethanolic and Petroleum ether extracts of leaves	Exhibited activity against *B. subtilis, B. pumilus, S. aureus, M. flavus, P. vulgaris, B. bronchiseptica*	Wasim *et al.* (1995)
Aqueous-ethanol extracts of stems and leaves	Very good antimicrobial activity against *S. aureus*	Borchardt *et al.* (2008)
Essential oil	Excellent activity against *C. sporogens, E. faecium, S. salivarius* subsp. *thermophiles, P. carotovorum* subsp. *carotovorum, P. savastanoi pv. phaseolicola*	Nissen *et al.* (2010)
	Modest activity against *A. hydrophyla, B. subtilis, B. natriegens, B. linens, B. thermosphacta, E. coli, F. suaveolens, M. luteus, S. aureus and Y. enterocolitica*	Novak *et al.* (2001)

The antibacterial activity of hemp seed oil, essential oil, and organic solvent extracts has been studied (Ali *et al.* 2012; Borchardt *et al.* 2008; Leizer *et al*. 2000; Nissen *et al.* 2010; Novak *et al.* 2001; Wasim *et al*. 1995). Ali *et al.* (2012) investigated seed oil, and petroleum ether, and methanol extracts of the whole hemp plant for their antimicrobial activity against two Gram positive organisms (*B. subtilis* and *S. aureus*), two Gram negative organisms (*E. coli* and *P. aeruginosa*), and two fungi (*Aspergillus niger* and *C. albicans*) using the cup plate agar diffusion method. They found that the seed oil produced pronounced antibacterial activity of inhibition against *B. subtilis* and *S. aureus*, moderate activity against *E. coli*, and high activity against *P. aeruginosa*. They were inactive against the two fungi tested. The petroleum ether extract of the whole plant exhibited pronounced antibacterial activity against both *B. subtilis* and *S. aureus* organisms, high activity against *E. coli*, and was inactive against *P. aeruginosa* and both fungi. The methanol extract of the whole plant also showed pronounced antibacterial activity against *B. subtilis*, low activity against *S. aureus*, and high activity against both Gram negative organisms, while being inactive against *A. niger* and having low activity against *C. albicans*.

Another study examined the inhibitory activity of freshly extracted essential oils from three fibre type hemp varieties (Carmagnola, Fibranova, and Futura) on microbial growth (Nissen *et al.* 2010). The results showed that essential oils of industrial hemp can significantly inhibit the microbial growth, depending on variety and sowing time. Novak *et al.* (2001) found that the essential oils of five different cultivars of hemp had modest antibacterial property.

Linking an antibacterial functional group with the cellulosic backbone of hemp fibre may offer opportunities to produce functionalized biopolymer for biomedical applications. Cassano *et al*. (2013) prepared material via esterification of hemp with 2-benzyl-4-chlorophenol, a germicidal agent, which was covalently coupled to cellulose backbone of hydrophilic fibers by a heterogeneous synthesis, to produce a functionalized biopolymer with a satisfactory degree of substitution. Its antibacterial activity in inhibiting *S. aureus* and *P. aeruginosa* growth in Petri dishes suggested that this biomaterial possesses an excellent *in vitro* antibacterial activity and so it can be efficiently employed in biomedical fields to ensure a protection against contaminations. The functionalized biopolymer interacts with metal ions because of its chelating functional groups. This feature makes the synthesized biomaterial a potential candidate for metal ions removal.

Negative results regarding antibacterial activity of hemp also have been reported (Sokmen *et al.* 1999; Yasmeen *et al.* 2012). Air-dried and finely ground samples of hemp seeds were extracted in methanol at 60 °C for 6 h, and the extract was tested against *S. aureus*, *B. cereus*, *B. catarrhalis*, *E. coli*, *C. perfringens* and *C. albicans.* The extract did not exhibit any activity against any of the microorganisms (Sokmen *et al*. 1999). Aqueous and alcoholic extracts of hemp were evaluated for their *in vitro* antibacterial activity against *P. mirabilis* by serial dilution methods (Yasmeen *et al.* 2012). Both the aqueous and alcoholic extracts of hemp did not show any antibacterial activity against *P. mirabilis.*

In general, cannabinoids, alkanoids, seed oil, essential oils, methanol extracts, ethanolic extracts, acetone extracts, and petroleum ether extracts of whole hemp plant or leaves showed antibacterial effect against a variety of bacteria. Hemp may have many applications in controlling microorganism; however, no products have been reported.

Antibacterial activity of hemp hurd

Lignin, the second most abundant natural compound after cellulose (Boudet and Grima-Pettenati 1996), is a high-molecular weight polymer of phenolic compounds that occurs naturally in plants. The phenolic components of lignin have been reported to inhibit growth of micro-organisms such as *E. coli*, *S. cerevisiae*, *B. licheniformis*, and *A. niger* (Baurhoo *et al*. 2008; Zemek *et al.* 1979). Some studies discovered that lignin in bamboo (Afrin *et al.* 2012), lignin in corn stover (Dong *et al.* 2011), as well as lignin in cotton stalks and bagasse (Nada *et al.* 1989) demonstrated potent antibacterial activity. The total amount of lignin in bamboo may vary between 26.8% to 30.1% of the weight (Sekyere 1994). Afrin *et al.* (2012) claimed that antibacterial agents of bamboo (*Phyllostachys pubescens*) are located in lignin (aromatic and phenolic functional groups in lignin). Phenolic acids and aldehydes identified from alkaline nitrobenzene oxidation of bamboo are vanillin, syringic acid, syringaldehyde, vanillic acid, p-hydroxybenzaldehyde, p-hydroxybenzoic acid, p-coumaric acid, acetosyringone, acetovanillone, and ferulic acid (Li *et al.* 2010).

Hemp hurds have high content of lignin (19 to 21%) and hemicellulose (31 to 37%), but lower amount of cellulose (36 to 41%) (Thygesen *et al.* 2007). Phenolic acids and aldehydes identified in hemp hurd are vanillin, syringaldehyde, p-hydroxybenzaldehyde, vanillic acid, syringic acid, p-coumaric acid, acetosyringone, and gallic acid (Gandolfi *et al*. 2013). It is clearly evident that the phenolic compounds identified in hemp lignin are similar to those in bamboo. Besides, cannabinoid content of fibre type hemp hurds was investigated by Cappelletto *et al.* (2001). The cannabinoid (Δ^9-THC, CBD, Δ8-THC, and CBN) content of the dust obtained from the top of the stems after the mechanical treatment can be up to 1.3% of dry matter. Considerable amount of cannabinoids present in hemp hurd as well as the phenolic compounds that hemp hurd might possess good antibacterial property.

Other Natural Fibre Plants

Among all the fibre producing plants, hemp has been the most predominantly investigated plant for bioactive components. Other fibre plants such as jute, bamboo, flax, sisal, kenaf, banana, and pineapple, have also been investigated and have shown some antibacterial activity.

Bamboo

Bamboo belongs to the family of Poaceae (grasses), sub-family (Bambusoideae) and tribe (Bambuseae) (Worobiec and Worobiec 2005). The main constituents of bamboo culms are cellulose, hemicellulose, and lignin, which account for over 90% of the total mass. It also contains about 2 to 6% starch, 2% deoxidized saccharide, 2 to 4% fat, and 0.8 to 6% protein. Alpha-cellulose, lignin, extractives, pentosan, ash, and silica content are increased with increasing age of bamboo (Chen *et al.* 1985; Yusoff *et al.* 1994).

It is well accepted that there are abundant biologically active components in bamboo, such as triterpenoids, saponins, and sterols (Chen *et al.* 2002). Several phenolic compounds have been identified in the culms and leaves. Composition and concentrations of soluble phenolic compounds (phenolic acids and flavonoids) in bamboo culms are affected by species, age and site (Keski-Saari *et al.* 2008).

Antibacterial performance of bamboo extracts was reported, where methanol, ethanol, and other common solvent extracts of bamboo culms, shavings, and leaves were tested against a wide variety of bacteria (Mulyono *et al.* 2013). Afrin *et al.* (2012) claimed that antibacterial agents of bamboo (*Phyllostachys pubescens*) are located in lignin, not in hemicellulose or other water-soluble chemical components. In this case, extraction was done with raw bamboo powder in water, dimethyl sulphoxide (DMSO), and aqueous dioxane, since DMSO and dioxane are regarded as commonly used solvents for hemicellulose and lignin respectively.

Jute

Jute fibre is obtained from two cultivated species *Corchorus capsularis* and *C. olitorius*. Cardiac glycosides, triterpenoids, sterols, phenolics, ionones, carbohydrates, and fatty acids have been reported from jute (Khan *et al.* 2006; Kohda *et al*. 1994). Mosihuzzaman *et al.* (1982) identified low molecular weight carbohydrates, inositols, lignin, glycosidic, and ester-linked phenolic acids in the bark, stick, and fibre of the jute plant. Analysis of lignin and cinnamic acids in jute using analytical pyrolysis and Fourier-transform infrared (FTIR) spectroscopy was carried out, and around 80 compound were identified (del Rio *et al*. 2007).

The antibacterial activities of the petroleum ether, methanol and ethyl acetate+water extracts from the jute plant sample were evaluated. The petroleum ether extract of jute leaves demonstrated activity against *E. coli*, *S. aureus*, and *Y. enterocolitica*. The ethyl acetate+water extract was effective against *G. candidum* and *B. cinerea* (Ilhan *et al*. 2007). Antibacterial activity of the jute plant also has been reported by other researchers (Adegoke and Adebayo-Tayo 2009; Patel Rashmika 2011). Farah *et al.* (2006) demonstrated the potential use of jute as an antibacterial agent against infections of *C. diphtheria*, *S. aureus, B. cereus*, *S. epidermidis*, and *K. rhizophila*.

Flax, Sisal, Kenaf, and others

Flax (*Linum usitatissimum*) belongs to the Linaceae family. Flax-seed contains many bioactive compounds, such as alpha-linolenic acid, lignans, and protein (Rubilar *et al*. 2010). Linseed oil or flax-seed oil showed good *in vitro* antibacterial activity against a number of microorganisms including *S. aureus*, *S. agalactiae*, *E. faecalis*, *C. albicans*, and *E coli* (Kaithwas *et al*. 2011). Antibacterial and antifungal activity of flax seed also has been reported by others (Guilloux *et al.* 2009; Rubilar *et al.* 2010; Xu *et al*. 2008).

Sisal belongs to the Agavaceae family. Fibres are obtained from leaves that are composed of 78% cellulose, 8% lignin, 10% hemicelluloses, 2% waxes, and about 1% ash by weight (Barkakaty 1976). Antibacterial activity of sisal plant was also reported in some literature (Dlamini Abednego *et al.* 2010; Santos et al. 2009). The hydroalcoholic extract obtained from sisal showed significant inhibition of *C. albicans* (Santos *et al.* 2009).

The kenaf plant (*Hibiscus cannabinus*) is composed of multiple useful components (*e.g*. stalks, leaves, and seeds) (Webber III and Bledsoe 2002). Antibacterial activity of Kenaf against *S. aureus* and *E. coli* was reported (Zakaria *et al.* 2011).

While cultivated primarily for their fruits, banana, and pineapple plants are also valuable source of plant fibre. Ethyl acetate, ethanol, and water soluble fractions of green banana peels, pulps, seeds, and inflorescences displayed high antibacterial and antioxidant activity (Fagbemi *et al*. 2009; Jain *et al.* 2011; Khan *et al.* 2010; Mokbe and Hashinaga, 2005; Padam *et al*. 2012). Pineapple stem waste exhibited antibacterial activity to some extent (Upadhyay *et al.* 2012).

POTENTIAL APPLICATIONS OF ANTIBACTERIAL HEMP

Contamination by microorganisms is of great concern in a variety of areas, such as medical devices, healthcare products, water purification systems, hospitals, dental office equipment, food packaging, food storage, and household sanitation (Patel *et al*. 2003). One possible way to manage microbial contamination is to develop materials with antimicrobial properties (Park *et al.* 2001). Application of hemp as drug and antibacterial agents have been reported (Moore *et al.* 2007).

Biomedical Applications

Biomedical application of polymer composites can be found in the form of implants and medical devices (Ramakrishna *et al*. 2001). In some applications the antibacterial property may increase the functionality of polymer composites, for example in wound dressing. These skin dressings should prevent loss of fluids, electrolytes, and other biomolecules from the wound and obstruct bacterial entry, but should also be permeable enough to allow the passage of discharges from pores or cuts. Hemp can be used in conjunction with suitable materials to meet these requirements. For example, polyurethane (PU) and chitosan are frequently used in wound dressings due to their excellent barrier properties and oxygen permeability (Khil *et al.* 2003; Mi *et al*. 2003). Hemp incorporated nanofibrous PU membrane, prepared by electrospinning, could be properly employed as wound dressings. Again, hemp incorporated asymmetric chitosan membrane may be a very useful wound dressing with the antibacterial capacity to prevent infection of broken skin. As well as the antibacterial property of hemp, its porous physical structure, air permeabilty, and absorbency capabilities would add advantageous features to wound dressing.

The lightweight, corrosion resistance, fatigue resistance, aesthetics, and ease of fabrication of polymer composite materials make them an ideal choice for modern limb systems (Ramakrishna *et al*. 2001). A large number of polymers such as polyethylene (PE), polyurethane (PU), polytetrafluoroethylene (PTFE), polyacetal (PA), polymethylmethacrylate (PMMA), polyethylene terepthalate (PET), silicone rubber (SR), polysulfone (PS), polyetheretherketone (PEEK), poly(lactic acid) (PLA), poly(glycolic acid) (PGA), and so on are used in various biomedical applications (Ramakrishna *et al*. 2001). Incorporating antibacterial hemp as filler in the polymer composites could provide protection against bacterial attachment. Hemp incorporated polymer composites can be an excellent choice for prostheses for external missing limbs such as legs and arms. Also, cannabinoids and alkaloids have the potential to be used as a drug to treat bacterial infection or may be used in conjunction with antibiotics to enhance their activity.

Food Packaging

In recent years, new food-packaging systems have been developed in response to trends in consumer preferences towards mildly preserved, fresh, tasty, and convenient food products with a prolonged shelf-life (Emamifar 2011). In addition, food-borne microbial outbreaks are driving a search for innovative ways to inhibit microbial growth in the foods while maintaining quality, freshness, and safety (Paola 2002). To provide this shelf-life extension, and to improve the quality, safety, and integrity of the packaged food, innovative active and intelligent packaging concepts are being developed. Examples of this are incorporating oxygen, moisture, and ethylene scavengers for oxygen, moisture, and ethylene sensitive foods, use of carbon dioxide or ethylene emitters in other foods, flavor imparting or scavenging chemicals, and antimicrobial agents for microbiological safety of food (Chinnan 2004). The application of antimicrobial agents to packaging can create an environment inside the package that may delay or even prevent the growth of microorganisms on the product surface and, hence, lead to an extension of the shelf life and/or the improved safety of the product. Antimicrobial packaging is a form of active packaging that interacts with the product or the headspace between the package and the food system, to obtain a desired outcome (Paola 2002). Although most of the antibacterial agents currently being used are usually artificial chemicals, natural plant material has the potential to be used in active packaging. For example, edible films incorporated with clove essential oil showed significant antibacterial activity against *L. acidophilus, P. fluorescens, L. innocua,* and *E. coli* (Gómez-Estaca *et al.* 2009). Similarly, hemp can be incorporated in food packaging composites, and be considered as ecofriendly. Hemp incorporated polymer composites formed by injection moulding can provide packaging materials with a wide range of shape and sizes for containing a range of foods including meat, salads, and ready-made food products. Essential oils of fibre type hemp may also have interesting applications in controlling spoilage by food-borne pathogens and phytopathogenic microorganisms.

Cosmetics

Hemp can be used for skin care and cosmetic due to the high content of oil, especially unsaturated fatty acids (Vogl *et al.* 2004). Antibacterial hemp in powder form can be incorporated into tooth powder, toothpaste, mouth-wash, toilet bars, antiseptic ointment, and foot powders. In hot weather, for example sweating and exercise generate a moisture-rich environment in shoes that stimulates overgrowth of both aerobic bacteria and fungi (Misner 2007). Antibacterial foot soakings may provide relief. Essential oil of hemp can also provide benefits in various cosmetics. An exposure and uptake assessment for Δ^9-THC from hemp oil cosmetics was conducted to address concerns about Δ^9-THC in cosmetics (Pless and Leson 2001). The results strongly suggested that even unrealistically extensive use of such products could not result in positive screening or confirmed urine tests for marijuana.

CLOSING STATEMENTS

Antibacterial activity of hemp and other fibre plants has been reviewed. The review suggests that natural fibre plants could serve as a potential source of antibacterial components and can be utilized effectively without being wasted. Cannabinoids, alkanoids, other bioactive compounds or phenolic compounds of lignin may contribute to the antibacterial character of hemp. Recently, a series of tests has been conducted on hemp hurd for its antibacterial activity (not published yet), and strong antibacterial activity is shown against *E. coli*. This finding reveals tremendous opportunity of hemp hurd to be used in functional applications. Intensive research is needed towards identification of active compounds for antibacterial effect and utilization of inexpensive materials in value-added diversified products with consideration into their antibacterial performance. Future work should focus on the development of new antimicrobial polymer composites to be used where contamination by microorganisms is of concern. Participation and collaboration of research institutes, industry, and government regulatory agencies will be the key for the success of antimicrobial polymer composites.

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