Chapter 2
Traditional and New Applications of Hemp

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Abstract Recent trends in natural resources, energy conservation, biomass conversion to chemicals, bioproducts and biofuels have renewed the interest on hemp as a new low-cost, sustainable, ecological, biodegradable, recyclable, and multi-purpose material. Hemp-based materials are indeed suitable substitutes for many fossil-based materials and applications.

The hemp plant *Cannabis sativa* Linn, referring to industrial hemp, is a high-yielding annual industrial crop grown, for the fibers from hemp stalk and for the oil from hemp seeds. Although hemp is a niche crop, hemp production is currently undergoing a renaissance. More than 30 countries grow hemp, with China being the largest hemp producing and exporting country. Europe and Canada are also important actors in the global hemp market.

Hemp has many better properties than other plant species, such as superior fiber length, strength and absorbency, interesting thermal and acoustic properties, excellent oil quality for both industrial and feed uses, environmental and economic benefits, and a myriad of applications. For millenia, hemp has been a source of fibers, proteins, and oilseed used worldwide to produce a variety of consumer products for the four fundamental human needs, i.e. food, shelter, clothes and energy.

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Traditionally, hemp as fiber plant has been used in the production of apparels, fabrics, papers, cordages, and building materials. For instance, hemp was found in cloth unearthed from the tomb of Pharaoh Alchanaten dating back to 1200 B.C. and the Guttenberg Bible was printed on hemp paper in 1456. The hurds, as waste byproduct of fiber production, were used for bedding of animals, the seeds to human nutrition, e.g. as flour, and the oil for a wide range of purposes, from cooking to cosmetics. Hemp has also been an important crop throughout human history for medicine, e.g. to treat various disorders for thousands of years in traditional Chinese medicine.

Other more recent applications include materials for insulation and furniture, automotive composites for interior applications and motor vehicle parts, bioplastics, jewelry and fashion sector, animal feed, animal bedding, e.g. mulch for horses and kitty litter, and energy and fuel production. Foods containing hemp seed and oil are currently marketed in worldwide for both animal and human nutrition. They also find applications in beverages, e.g. in beer and wine industries, and in neutraceutical products. Hemp oil is also used for cosmetics and personal care items, paints, printing inks, detergents, and solvents. It is estimated that the global market for hemp consists of more than 25,000 products.

Currently, the construction and insulation sector, paper and textile industries, and food and nutrition domains are the main markets while the cosmetics and automotive sector are growing markets. Innovative applications, e.g. in the medical and therapeutic domains, cosmeceuticals, phytoremediation, acoustic domain, wastewater treatment, biofuels, bio-pesticides and biotechnology, opens new challenges. Hemp is also the object of numerous fundamental studies.

This chapter provides an overview of the traditional and new uses of industrial hemp.

Keywords Hemp applications · Textiles · Paper · Building materials · Food · Beverages · Cosmetics · Biocomposites · Energy production · Biofuel · Environmental uses

2.1 Introduction

Hemp is a dicotyledonous plant from the order of Rosales, from the family of Cannabaceae, genus *Cannabis*, like marijuana (Bouloc 2013). Hemp originated from Asia and is considered one of the oldest domesticated crops known to man (De Candolle 1883; Vavilov 1992; Lu and Clarke 1995; Amaducci and Gusovious 2010; Allegret 2013; Amaducci et al. 2015).

Hemp-based products such as bits of hemp fabric have been discovered in tombs dating back to 8000 B.C. (Lu and Clarke 1995; Bouloc 2013). Hemp was also cultivated 4500 years ago in China for fiber, seeds and oil production for multiple applications, e.g. cords imprinted on ancient pottery shards containing hemp residues and piece of paper made from hemp have been discovered (Vavilov 1992;

Roulac 1997; Ranalli 1999; Bouloc 2013). According to ancient Chinese writings, extracts of hemp were also used to treat a wide range of diseases. In Ancient Egypt, the pharaohs also used hemp, e.g. hemp was found in cloth unearthed from the tomb of Pharaoh Alchanaten dating back to 1200 B.C.

In the 600 s, Germans and Vikings made paper, sails and rope from hemp. The Guttenberg Bible was printed on hemp paper in 1456 (Lu and Clarke 1995). In sixteenth to eighteenth century, hemp was a major fiber crop in Europe, Russia and North America (Vavilov 1992; Lu and Clarke 1995; Gibson 2006; Bouloc 2013).

President George Washington grew hemp (Fike 2016) and Americans were legally bound to grow hemp during the Colonial Era and Early Republic (source: Hemp Industries Association). In Colonial days, farmers indeed grew hemp and processed it to make paper, braid ropes, sew clothing, and manufacture canvas sacks. The first American flag was made from it and the Declaration of Independence drafted on hemp paper in 1776. Pionners used hemp covered wagons (Fike 2016).

For thousands of years, hemp fibers were used for clothing and shoes, cordages, carpets and tarps, maritime ropes, sails and nets, and paper production, the hurds for bedding of animals and as straw for agricultural purposes and other uses, e.g. as waste to be burned and more recently as fuel to power farm equipment, the seeds as nutrition, and the oils for a wide range of purposes, from cooking to personal care. The leaves were also used for mulch, composting and animal bedding (De Candolle 1883; Vavilov 1992; Roulac 1997; Ranalli 1999; Ranalli and Venturi 2004; Amaducci 2005; Gibson 2006; Milanovic et al. 2012; Allegret 2013; Bouloc 2013).

In the middle of nineteenth century, hemp cultivation decreased with the disappearance of the sailing navy and competition from other natural fibers such as cotton and jute for textile applications, and later due to intensive development of synthetic fibers (Small and Marcus 2002; Ranalli and Venturi 2004; Milanovic et al. 2012). In the 1930s, cultivation was forbidden in most Western countries and in North America due to the fact that both hemp and marijuana come from the same genus and species plant, and this introduced a lot of confusion and social, political and moral controversies (Amaducci 2005; Holler et al. 2008; Bouloc 2013; Sawler et al. 2015; Cherney and Small 2016; Chandra et al. 2017; Das et al. 2017; Johnson 2018).

Indeed, hemp, i.e. plant species *Cannabis sativa* L., became a controversial crop due to its genetic closeness to THC-producing plants. THC, delta-9-tetrahydrocannabinol, is the chemical most responsible for the phsychoactive properties in marijuana. THC is a psychoactive ingredient present in all hemp varieties to some extent. Marijuana, so-called medical cannabis, contains about 10–30% of THC while hemp refers to the non-psychoactive varieties of *Cannabis sativa* L. (Bouloc 2013; Sawler et al. 2015; Pacaphol and Aht-Ong 2017; Żuk-Gołaszewska and Gołaszewski 2018). Hemp, referred to industrial hemp, has less than 0.2–0.3% THC but contains high levels of cannabidiol (CBD). However, industrial hemp is often incorrectly associated with hemp for narcotics.

Schultes wrote: "*Hemp is a green, very abundant and ubiquitous plant, economically valuable, a versatile and multi-purpose product, possibly dangerous and certainly in many ways mysterious*" (Schultes 1970). This definition is pertinent in describing the valuable but contradictory nature of this industrial crop.

The 1990s marked the renewal of hemp cultivation from an agricultural, industrial and scientific point of view throughout the world (Bócsa and Karus 1998; Small and Marcus 2002; Ranalli and Venturi 2004; Sponner et al. 2005; Kozlowski et al. 2005; Figueiredo et al. 2010; Thomas et al. 2011; Fike 2016). Indeed, growing interests in the commercial cultivation of hemp and other "forgotten fibers" in Europe and North America have emerged since the 1990s, mainly due to the increasing consideration of natural resources, energy conservation, and biomass conversion to bioproducts and biofuels (Roulac 1997; Gibson 2006; Kostić et al. 2003; Ranalli and Venturi 2004; Sponner et al. 2005; Kozlowski et al. 2005; Figueiredo et al. 2010; Thomas et al. 2011; Faruk et al. 2012).

Since 1992, France, The Netherlands, England, Spain and Germany have passed legislation allowing for the commercial cultivation of low-THC hemp. Two years later, Canada also proposed regulations for hemp cultivation, about 60 years after its prohibition.

Hemp is then considered as a valuable crop with particular agronomic characteristics that provided raw materials, i.e. fibers and oil, suitable for multiple potential applications. It quickly found concrete industrial applications, e.g. hempcrete was becoming a viable alternative to traditional building materials, particularly for insulation, panels and roofs (Small and Marcus 2002; Amaducci 2005). Using environmental-friendly and sustainable hemp-based materials for building insulation and construction was a pertinent approach to address reduction in carbon dioxide emission.

To build cars, processing processes allowed hemp fibers to be incorporated into biocomposites that are lighter than steel and much stronger. Another valuable field was the manufacture of biodegradable and non-toxic plastics based on hemp, referred as bioplastics. Indeed, industrial hemp has become an attractive biomass for bioplastic production although this material is typically resistant to enzymatic hydrolysis and direct fermentation by microorganism, due to the complex interactions of cellulose, hemicellulose lignin, and pectin.

The hemp oil was also used for food uses and for applications in cosmetics and personal care. All these areas continue to be exploited today and there are also other very active and innovative industrial markets for hemp-based materials and products (Fig. 2.1).

Currently, more than 30 nations grow industrial hemp as an agricultural commodity with high potential (Food and Agriculture Organization of the United Nations, www.faostat.fao.org). This plant is being mainly cultivated in China, the largest supplier in the world, in North Korea, Chile, Russia, Canada and Europe (Bouloc 2013; Amaducci et al. 2015; Salentijn et al. 2015; Żuk-Gołaszewska and Gołaszewski 2018). France is the top European producer of hemp with an area of cultivation around 12,000 ha (Morin-Crini et al. 2018, 2019). Hemp cultivation and hemp industry are also important in Lithuania, Germany, Italy, Poland, The Netherlands, Romania, Estonia, Hungary, Spain, and England (Żuk-Gołaszewska and Gołaszewski 2018).

Its production is however strictly controlled under existing National and European laws. In most European countries, the current upper legal limit for cultivation of industrial hemp for fiber and seeds production is 0.2% THC on dry basis (Russo and Reggiani 2013; Salentijn et al. 2015; Frassinetti et al. 2018). This

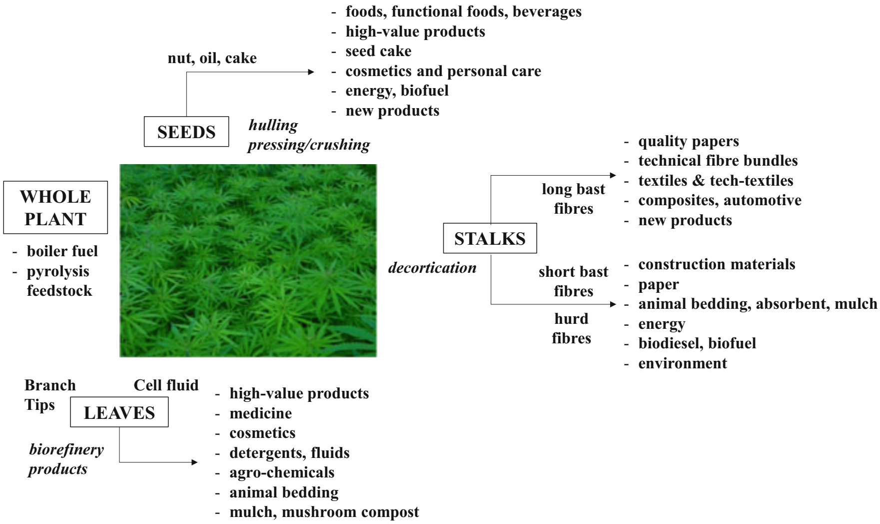

Fig. 2.1 Modern applications of hemp

restriction has reduced the number of varieties available for its cultivation. Hemp is currently subsidized by the European Union for non-food agriculture and research purposes, and a considerable initiative for its further development in Europe is underway.

Hemp is considered as a low-cost, ecological, sustainable and multi-use plant (Faruk et al. 2012; Shahzad 2012; Bouloc 2013; Bono et al. 2015; Johnson 2018). An important advantage is the fact that the entire plant, i.e. seeds and plant stem, is recoverable (Roulac 1997; Johnson 1999; Ranalli and Venturi 2004; Sadrmanesh and Chen 2019). Another advantage is hemp versatility, being useable in various forms, e.g. fibers, felts, powders, shives, and seed products including seeds themselves, oil and oil cake. All these products can be used for a myriad of applications as reported in Fig. 2.1.

The global market for industrial hemp has more than 25,000 products in nine main submarkets: textiles, agriculture, automotive, food and beverages, paper, furniture, construction, recycling, and personal care. Johnson (2018) recently reported that the sales of hemp based product in the U.S. alone is about $600 million dollars in 2017.

From a scientific point of view, hemp is also the object of numerous fundamental studies and a great deal of research is being conducted around the world. An indication of the widespread exploitation and constantly growing importance of this plant is the total of over 3750 scientific articles published between in the last 5 years (ISI Web of Science database). It is interesting to note that a majority of these investigations have been done in China, Korea, North America, Russia and Europe.

This chapter provides an overview of the traditional and new uses of industrial hemp, based on a large number of relevant references published over the last decade (Table 2.1).

Table 2.1 Applications of industrial hemp: selected publications during the last decade

Topics	References
Agriculture – Agrochemistry	Kolodziejczyk et al. (2012), Bouloc (2013), Mukhtar et al. (2013), Isman (2015), Bedini et al. (2016), Pavela and Benelli (2016), Abé et al. (2018), Benelli et al. (2018) and Fiorini et al. (2019)
Mulch and animal bedding	
Animal feed, birdseeds	
Organic agriculture, bio-fertilizers	
Insect pest management, eco-friendly insecticide/herbicide	
Biofuels – Bioenergy	Burczyk et al. (2008), Ahmad et al. (2011), Li et al. (2010), Sipos et al. (2010), Kreuger et al. (2011), Prade et al. (2011, 2012), Gomes (2012), Finnan and Styles (2013), Rehman et al. (2013), Kuglarz et al. (2014, 2016), Fernando et al. (2015), Das et al. (2017) and Schluttenhofer and Yuan (2017)
Boiler fuel, solid fuel, pellets	
Biodiesel, bioethanol, methanol	
Biogas: methane, biohydrogen	
Electricity	
Building materials	Elfordy et al. (2008), Arnaud and Gourlay (2012), Ip and Miller (2012), Amziane and Arnaud (2013), Bouloc (2013), Collet et al. (2013), Pretot et al. (2014), Walker and Pavía (2014), Walker et al. (2014), Abd Rashid and Yusoff (2015), Cigasova et al. (2015), Latif et al. (2015), Ingrao et al. (2015), Aït Oumeziane et al. (2016), Arizzi et al. (2016), Fangueiro and Rana (2016), George et al. (2016), Jonaitiene and Stuoge (2016), Kinnane et al. (2016), Niyigena et al. (2016), Fernea et al. (2017), Gourlay et al. (2017), Kiruthika (2017), Liuzzi et al. (2017), Mazhoud et al. (2017), Mirski et al. (2017), Chernova et al. (2018), Jiang et al. (2018), Kallakas et al. (2018), Moujalled et al. (2018), Nováková (2018), Pichardo et al. (2018), Pittau et al. (2018), Usmani and Anas (2018), Iucolano et al. (2019) and Jami et al. (2019)
Insulation, hemp wool, paneling, fiberboard	
Concrete, cement blocks, mortar	
Composites – Furniture	Faruk et al. (2012), Shahzad (2012), Bhavani (2015), Bono et al. (2015), Cigasova et al. (2015), Fernando et al. (2015), Pil et al. (2016), Ummartyotin and Pechyen (2016) and Gallos et al. (2017), Lamberti and Sarkar (2017), Liu et al. (2017), Mirski et al. (2017), Nunes (2017), Nurazzi et al. (2017), Chernova et al. (2018), Karaduman et al. (2018), Musio et al. (2018), Sarasini and Fiore (2018), Sepe et al. (2018), Spierling et al. (2018), Usmani and Anas (2018) and Väisänen et al. (2018)
Green composites, biocomposites	
Plastic composites	
Furniture industry	
Nanomaterials	
Cosmetology – Hygiene	Bertoli et al. (2010), Kolodziejczyk et al. (2012), Ionescu et al. (2015), Hartsel et al. (2016), Ligeza et al. (2016), Bonini et al. (2018)
Oils, lotions, moisturizer, body care products	
Shampoos, bath gels, soaps, anti-microbe hand soap	
Essential oils, beauty products	

(continued)

Table 2.1 (continued)

Topics	References
Environmental purposes	Kostić et al. (2008, 2010, 2014, 2018), Pejić et al. (2008, 2009, 2011), Rosas et al. (2009), Tofan et al. (2009, 2010a, b, c, 2013, 2015, 2016a, b), Yang et al. (2011, 2012), Vukčević et al. (2012, 2014a, b, 2015), Zou et al. (2012), Cassano et al. (2013), Rezić (2013), Sun et al. (2013), Balintova et al. (2014), Feng and Zhang (2015), Lupul et al. (2015a, b), Kyzas et al. (2015), Wang et al. (2015), Ahmad et al. (2016), Bugnet et al. (2017a, b), Loiacono et al. (2017a, b, c, 2018a, b) and Saxena et al. (2020)
Compost, growth medium	
Elimination of contaminants: metals	
Phytoremediation, phytoextraction	
Activated carbon production	
Water and wastewater treatment	
Air/oil filtration	
Food industry – Beverages	Yin et al. (2008, 2009), Kolodziejczyk et al. (2012), Bouloc (2013), Russo and Reggiani (2013), Girgih et al. (2014c), Malomo et al. (2014), The and Birch (2014), Dunford (2015), Malomo and Aluko (2015a, b), Andre et al. (2016), Fike (2016), Hartsel et al. (2016), The et al. (2016), Chandra et al. (2017), Korus et al. (2017), Mikulcová et al. (2017), Pihlanto et al. (2017), Frassinetti et al. (2018), Hadnađev et al. (2018), Johnson (2018), Devi and Khanam (2019a, b), Fathordoobady et al. (2019), Fiorini et al. (2019), King (2019), Mamone et al. (2019), Mikulec et al. (2019), Wang and Xiong (2019) and Zajac et al. (2019)
Nutrition and beverages: salad oil, margarine, granola, protein flour, beers, wines	
Functional food, nutritional supplement	
Nutraceutical products	
High-value products: fatty acids, nutrients, lecithin	
Animal nutrition, feed additives	
Paper	Harris et al. (2008), Barberà et al. (2011), Bouloc (2013), Miao et al. (2014), Feng and Zhang (2015), Danielewicz and Surma-Slusarska (2017), Przybysz Buzala et al. (2017), Yu et al. (2017) and Bajpai (2018)
Paper pulp, cardboard, packaging	
Cigarette paper	
Printing papers, newsprint	
Fine and specialty papers	
Technical filter paper, filters	
Medicine	Rodriguez-Leyva and Pierce (2010), Cassano et al. (2013), Richard and Dejean (2013), Russo and Reggiani (2013), Girgih et al. (2014a, b), Cherney and Small (2016), Hartsel et al. (2016), Parian and Limketkai (2016), Pathak et al. (2016), Bonini et al. (2018), Zhou et al. (2018), Devi and Khanam (2019a), Fathordoobady et al. (2019), Fiorini et al. (2019), Mamone et al. (2019) and VanDolah et al. (2019)
Active/psychoactive substances: cannabinoids, terpenes	
Drugs: glaucoma, vomiting, spasms	
Antibacterial products	
Textiles & Tech-Textiles – Ropes – Furniture	Amaducci and Gusovious (2010), Müssig (2010), Bouloc (2013), Kostić et al. (2014), Pil et al. (2016), Zhang et al. (2016), Bran et al. (2017), Lamberti and Sarkar (2017), Mirski et al. (2017), Rijavec et al. (2017), Gedik and Avinc (2018) and Miller (2018)
Fabrics, bacteria-fighting fabrics	
Clothes, sport clothing, military clothes, socks, knitted	
Underwear, T-shirt	
Bags, canvas bags, shoes	
Rops, twines, nets, carpets, nonwoven, geotextiles	

2.2 Hemp Products

Hemp production can provide social, economical, environmental, agronomic and industrial benefits.

From a social and economic point of view, hemp cultivation is a vector of development for local agricultural resources in emerging countries and an industrial output for crops in developed countries. Both on the production and demande sides, there are in each country an active movement towards the development of a hemp industry due to a multitude of potential benefits often cited (Bócsa and Karus 1998; Johnson 1999; Fike 2016; Żuk-Gołaszewska and Gołaszewski 2018), as an increase efficiency compared to others inputs for some industrial uses such as paper production, health benefits of both hemp seed and hemp oil consumption, and a competitive use as an input in textile manufacturing or furniture.

From an environmental point of view, hemp is one of the most efficient plants known for its ability to utilize sunlight and capture large quantities of CO_2 to photosynthesize, with an annual growth up to 5–6 m in height. Hemp is more environmentally friendly than traditional crops (Fike 2016; Żuk-Gołaszewska and Gołaszewski 2018).

From an agricultural point of view, hemp is considered as an excellent crop for sustainable agriculture (Żuk-Gołaszewska and Gołaszewski 2018). Indeed, the hemp cultivation has always been considered a good rotational crop because of its beneficial effect on following crops. Its cultivation helped to replenish the soil and did not require much weed control (Bócsa and Karus 1998). Gorchs et al. (2000) previously reported that an increased yield is obtained when wheat grown after hemp.

On the production side, hemp is also appreciated by organic growers for its adaptability to a wide range of agronomic conditions, ease of production, and rapid growth, e.g. after sowing, cultivation is not difficult. Hemp requires low fertilization and irrigation is not necessary. The crop requires only rarely the use of plant protection products. Herbicides are not considered necessary because hemp's fast growth, which results in weed suppression (Fike 2016; Sandler and Gibson 2019).

O'Brien and Arathi (2019) recently pointed out that, being wind pollinated, dioecious and staminate hemp plants produce large amounts of pollen that are attractive to bees. While hemp does not produce any nectar, the pollen rich nature of the flowers can make hemp an ecologically valuable crop.

Industrial hemp is cultivated to yield four products: the fiber, the seed and its extracted oil, and the bioactive substances from the seeds, seed cakes and leaves, the main product being the bast fiber (Sadrmanesh and Chen 2019). It is important to note that, for millennia, hemp was cultivated for (bast) fiber, mainly for textile and clothing applications while hurds were considered as byproducts of the fiber production. Indeed, hemp was traditionally known as a fiber plant and most historical cultivation of the plant was with fiber use in mind. Although consuming, the use of seeds and oil was not widespread.

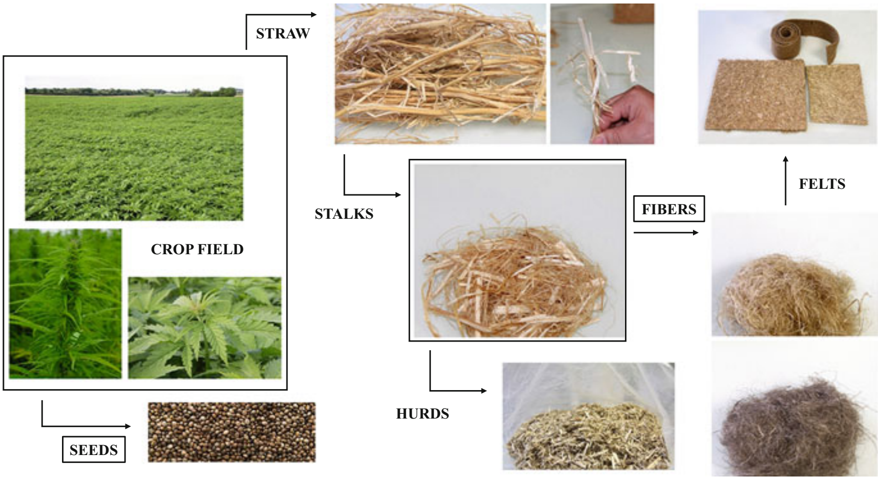

Fig. 2.2 Industrial hemp products; *Cannabis sativa* L. is the source of two types of natural fibers: long bast fibers in fibrous form and woody short core fibers, called hurds or shives, in granular form; the hemp stem photography shows bark, secondary bast fibers and woody core. (Source: G. Crini, Chrono-environnement, Besançon, France)

Nowadays, hemp can be grown for both fiber and seed harvesting (Fig. 2.2). Fiber is still the main product derived from hemp straw while the principal product made from hemp seeds today is undoubtedly the seed oil. Different hemp cultivars produce variable quantities and qualities of fiber, i.e. long bast fibers or short core fibers, as well as seed size and oil composition (Bócsa and Karus 1998; Karus and Vogt 2004). There are mainly two groups of Cannabis varieties being cultivated today (Żuk-Gołaszewska and Gołaszewski 2018): varieties primarily cultivated for their stalks, i.e. fibers used for construction material, clothing or animal related purposes, and varieties grown for seeds from which oil is extracted, e.g. for breeding and food.

Hemp can also be cultivated as dual-purpose crop that implies that both fibers and seeds can be processed. This practice has an impact on quality and quantity of fiber, e.g. a dedicated fiber crop yields the highest quality bast fiber for textiles and composites (Bouloc 2013). The yield and quality of hemp biomass are largely determined by the genetic background of the hemp cultivar. They are also strongly affected by environmental factors such as temperature and photoperiod (Salentijn et al. 2015, 2019).

Harvesting hemp fiber is however a bit tricky. Machinery has to be adapted to deal with the plant because the fibers can wrap among a harvester's moving parts, leading to possible mechanical failures. In addition, harvester knifes and blades must be kept sharp and in good condition in order to cut through the hemp stalk. Figure 2.3 shows a modern French forage chopper for cutting and windowing hemp. The preparation of the fiber is also a delicate activity that requires special know-how and machinery (Bócsa and Karus 1998; Karus and Vogt 2004; Münder et al. 2004; Fike 2016).

Fig. 2.3 A modern French forage chopper for cutting and windowing hemp. (Source: G. Chanet, Eurochanvre, Arc-les-Gray, France)

The fiber is divided into three fractions during mechanical processing: the short and long bast fiber bundles and the hurds/shives (Fig. 2.2). Hemp stem consists of approximately 20–40% of bast fibers and 60–80% of hurds, depending on variety or usage type, and planting density (Stevulova et al. 2014; Sadrmanesh and Chen 2019). The outside of the stem is covered with bark. Inside the stems are bast fibers and the woody core. The separation of the bast fiber is carried out through defiberization or decortication using specialized machineries, i.e. breaking the woody core of the stems into short pieces and separation of bast fiber from the hurds. The hemp fibers are situated in the bast of the hemp plant (Small and Marcus 2002; Hautala et al. 2004; Bouloc 2013).

The byproduct of the hemp stem obtained after the industrial defiberization process is the hurd, a short fibre which typically contains 20–30% lignin. In contrast to the high quality of bast fibers, the hurds or shives are the least valuable part of the plant, chemically close to wood. The industrial process also provides dust (10–15%) that can be find used as fuel and soil improver in powder form, or as granulated animal bedding.

There are two types of bast fibers: primary fibers, make up 70–90% of the bast, which extend nearly the entire length of the stalk and are coarser, and secondary fibers, 10–30% of the bast fibers, which are shorter, finer fibers that are found next to the wood core. The long, strong bast fibers are similar in length to soft wood fibers and are very low in lignin content while the short core fibers, more lignified, are more similar to hard wood fibers. Primary bast fibres are the most valuable part of the stalk. Low stand density of hemp crop and/or use of different genotypics favors development of secondary bast fibres.

Technical fibers are characterized with heterogeneous chemical composition and fairly complicated structure. The main constituents are cellulose, hemicelluloses and lignin, while minor components such as pectins and waxes are regarded as surface impurities (Kozlowski et al. 2005; Sponner et al. 2005; Ansell and Mwaikambo 2009; Thomas et al. 2011; Placet et al. 2014, 2017; Sadrmanesh and Chen 2019).

The fiber length and cellulose and lignin content are key quality parameters. As member of the bast fiber family, hemp contains over 75% of cellulose and less than 10 to 12% of lignin, compared with 60% and 30% respectively for wood. The bast fibers contain higher amounts of cellulose than the hurds. Given their differing physical properties, the two types of fibers have different ideal end uses (Bismarck et al. 2005; Thomas et al. 2011).

Most hemp oils available on the market are produced by cold pressing because of the simplicity of this method and its low serial production cost. However, only 60–80% of the oil can be recovered. There are other technologies such as soxhlet extraction using solvents, e.g. ethanol, n-hexane and petroleum ether, ultrasound-assisted extraction, techniques using supercritical carbon dioxide or microwave-assisted extraction (Da Porto et al. 2012; Chang et al. 2017; Subratti et al. 2019). In general, each extraction technique does not affect the fatty acids composition of the oils.

Da Porto et al. (2012), comparing the soxhlet extraction using n-hexane with supercritical carbon dioxide extraction, showed that a higher oil yield was achieved by the former method. Supercritical carbon dioxide extraction of oil depends on temperature, pressure and the size of hemp seed particles. Compared to cold pressing, the main disadvantages of this technique are high costs (expensive equipment) and high time costs. Solvent extraction is efficient but it requires longer extraction time compared to cold pressing and mostly it involves the use of organic solvents.

Subratti et al. (2019) recently proposed liquefied dimethyl ether as a green solvent for the extraction of hemp seed oil from hulled hemp seeds. The authors showed that the resulting yields were higher using liquefied dimethyl ether in comparison to conventional organic solvents. The oil was acquired in high purity. The process developed is simple to set up, affordable to use in any laboratory, does not require the use of a rotary evaporator, economical, and allows an easy recovery of the dimethyl ether without traces of solvent remaining in the crude. Indeed, dimethyl ether evaporates quickly at room temperature without leaving any residual solvent. The absence of applied heat is interesting because it preserves the integrity of the oil.

2.3 Hemp Fibers in Industrial Applications

From an industrial point of view, industrial hemp is a valuable raw material due to its natural origin, abundancy, renewable character, and mostly considered as a multiple-use plant with great potential (Fike 2016). Hemp fibers are suitable replacements for a variety of fossil-based products or applications. They are also valuable for various other reasons: their low cost, low carbon footprint, interesting life cycle analysis, low greenhouse gas emissions, etc.

All the hemp-based products mentioned above find a wide range of applications ranging from textiles and papers, to insulation and building materials, foods and beverages, cosmetics, livestock feed and bedding, and moulded plastics.

Traditionally, bast fibers were used to produce fabrics and textiles, bags and hard-wearing fabrics, twines, ropes, and paper. These fibers are now used in the manufacture of fine and specialty papers, insulation products, fiber-reinforced composites and bioplactics.

An important example is hempcrete/hemp-lime, perhaps the most researched bio-based building material. This material is a mixture of hurds and lime products used commonly in the construction sector, e.g. as a lightweight insulating material, hurd board, additive to bricks or loam construction, or as pour-in insulation.

Hemp is also used in plastics and composites for use as a fiberglass alternative by the automotive and aviation sectors. Hemp fibers, as eco-friendly material, are good candidates as a (partial) substitute for synthetic fibers such as glass, carbon or metallic fibers. Fine and specialty paper prepared from hemp can be used for making cigarettes. Hurds find applications as horse bedding or for bedding of small animals. Traditionally, the woody core was burnt for heating or to fuel the steam engines.

The oil extracted from the hemp seeds and their derivatives are most commonly used in various food-processing applications, nutritional supplements or as animal feed. The oil has also been considered for cosmetic applications, personal care products and skin care owing to its high polyunsaturated fatty acid content. Cannabinoid-based derivatives and other biological active substances are used by the pharmaceutical industry.

An interesting aspect of the cultivation of hemp is that hemp can be grown on polluted soil and can contribute to phytoremediation. In the last decade, hemp has been proposed as complexing material for pollutant removal. Hemp is also considered a suitable biomass crop for energy production or biodiesel.

All these applications are detailed in the following sections.

2.3.1 Textiles, Fabrics and Furniture

Hemp fiber has served humanity for thousands of years to create textiles, fabrics, ropes, yarns, rugs, and canvas. The fiber can be spun, then woven or knitted into many fabrics suitable for durable and comfortable clothing. Hemp fiber was indeed a common material for clothing because of its durability and versatility until the cotton industry grew stronger all over the world gained (Small and Marcus 2002; Liberalato 2003; Wang et al. 2003; Kozlowski et al. 2005; Sponner et al. 2005; Thomas et al. 2011; Bouloc 2013).

Hemp fiber is very strong compared with other natural fibers such as cotton, flax and nettle. So, historically, the fiber has also long been widely used in ropes, rigging, net, and sail production. Other advantages are its flexibility, strength, and resistance to water damage. Thus, in past centuries, hemp was extremely important to the Navy, the shipping trade, and also fishing. Christophe Colomb sailed to America on ships rigged with hemp (Bouloc 2013). The oldest known woven fabric was made from hemp, as were Levi Strauss' original denim jeans, and the first American flag.

Nowadays, hemp can be used to make a variety of similar but more durable fabrics than cotton (Amaducci and Gusovious 2010; Müssig 2010; Bouloc 2013). Numerous consumer brands such as Adidas, Patagonia, and commercial channels have added hemp products to their offer that help to popularized hemp as a clothing fibre or accessory.

Currently, clothing is a high profile market for hemp. Hemp fibers find numerous applications in textiles and the possibilities for hemp fabrics are immense: apparel, jeans, sport clothing, bags, hats, cushion covers, blankets, shoes, socks, accessories, ropes, yarns, rugs, furniture and home furnishings, and also hemp jewelry, e.g. bracelets, necklaces, anklets, rings, watches, and other adornments (Amaducci and Gusovious 2010; Müssig 2010; Bouloc 2013; Kostić et al. 2014; Bhavani 2015; Pil et al. 2016; Zhang et al. 2016; Bran et al. 2017; Lamberti and Sarkar 2017; Mirski et al. 2017; Rijavec et al. 2017; Gedik and Avinc 2018).

Textiles are easy to produce, durable, breathable, versatile, biodegradable, having strong thermal qualities. Fabrics have the best capacity ratio compared to other fibers, meaning they keep the wearer cool in the summer and warm in the winter. Preference for hemp textiles in summer is often associated with their excellent hygienic properties. However, natural fibers without modification do not provide good UV protection. The fabrics are also anti-microbial and hypoallergenic, as well as resistant to mold. Fibers are also more resistant to weather and ultraviolet rays than cotton and silk. Hemp clothing is stronger and more durable that cotton clothing and does not deform as easily. Apparel made from hemp merge easily with dyes and do not discolor easily. No difference between hemp and cotton fabrics in terms of colorfastness to crocking, oily stain release, flammability, tearing strength, breaking strength and elongation, as recently pointed out by Lamberti and Sarkar (2017). Fibers can also be mixed with other materials to create clothing hybrids, e.g. fibers can be blended with cotton or linen for specific textures and performance.

For all these reasons, hemp is also an eco-friendly fabric for upholstery and furniture: home furnishing textiles, seating, tables, fashion accessories, mirrors, wall decorations, decorative objects, etc. Finished goods such as clothing, shoes and hats are made from 100% hemp or combined with other natural or synthetic fibers. Figure 2.4 shows a hemp reusable bag made from 100% fibers. Hemp is also a viable and excellent fiber for making rugs, pure hemp carpets, and similar textiles. However, two main problems often cited are their primarily higher cost and the need for manufacturing machinery to be adapted.

Cordage is an age old use for hemp fiber. While its use in the marine world has largely being replaced by cheaper, long-lasting and lighter synthetics, hemp rope still has its uses. It is well-known that, due to its coarser texture, hemp rope can bind against itself for better knot stability, and this is useful in some situations. Hemp yarn is used for crafted jewelry because it is smooth, consistent, strong and comfortable in contact with the skin. Hemp twine is also interesting in crafting, gardening and landscaping.


Fig. 2.4 A hemp green bag. (Source: G. Chanet, Eurochanvre, Arc-les-Gray, France)

Hemp oil is also an interesting product for furniture, leather or wooden floor, e.g. Wise Owl Hemp. Pure oil, completely free of solvents or other chemical additives and preservatives, can be used to seal raw wood and furniture pieces. The advantages cited are: 100% natural, safe quality food, biodegradable, easy to use, both interior and exterior use, conservation of the initial color of wood, water and alcohol resistance, ideal for food surface, etc. Hemp oil for furniture is derived from the same pressed hemp seeds used for food grade edible oils, the only difference being the level of amino acids, which affect the drying time. The odor of the oil is much like crushed walnuts. Hemp oil may be used on finished wood to clean and protect or on unfinished wood to bring out the richness of the wood grain. It makes an excellent sealant over stained furniture.

However, although the hemp markets for clothing, furniture, luxury and fashion have seen a strong increase in popularity, the markets for specialty fibers tend to be cyclical. In addition, due to the rise in the industrial use of cotton followed by synthetic fibers in Europe, users had to turn to importing hemp, particularly from Asia. Nevertheless, several European companies and cooperatives, particularly in France, are carrying out several research and development programs for the reintroduction of European hemp into the textile industry because the possibilities for hemp fabrics are immense.

2.3.2 *Paper*

Historically, hemp has been used to make paper for thousands of years. In ancient China, hemp fiber was primarily produced for use in paper scrolls (Robinson 1996). As already mentioned, the first copies of the Bible were made of hemp paper and the American constitution was written on hemp paper (Ranalli and Venturi 2004). Hemp paper was more resistant to decomposition, stronger, especially when wet, less prone to yellowing than tree based paper (Harris et al. 2008; Ranalli and Venturi 2004; Bouloc 2013).

After the "rediscovery" of hemp in Europe in the 1990s, hemp fibers were mainly used for the manufacture of special pulp and paper. Hemp as non-wood fiber is indeed an ideal yield raw material for making specialty paper due to its high-quality physical properties of its pulp, and its tensile strength (Ranalli and Venturi 2004; Harris et al. 2008; Barberà et al. 2011; Bouloc 2013; Miao et al. 2014; Feng and Zhang 2015; Danielewicz and Surma-Slusarska 2017; Przybysz Buzala et al. 2017; Yu et al. 2017; Bajpai 2018).

Compared to conventional wood paper, hemp paper has superior qualities like higher strength, length and fineness. Hemp's long bast fibers makes a fine quality paper that is naturally acid free. Hemp paper uses less chemicals in production than tree based paper. It does not become yellow and brittle or disintegrate over time like conventional paper. It is a faster and more efficient way of growing fiber than the use of trees. The paper is also of a high-quality and durable for long term storage for forms, currency paper and cigarettes production. However, it is more expensive, i.e. the cost of hemp pulp is three to six times higher compared to conventional wood-based pulp production. This can be explained by the fact that the use of hemp in papermaking is mainly concentrated on bast fibers, the woody core of the plant being often considered as waste. The bast fibers are only a small part of the plant stem (hemp stalk averages around 20–30% bast fibers) and separation tends to lead to high production costs. Another difficulty which causes an increase of the hemp pulp price is that the hemp is harvested once and needs to be stored all year long.

The applications are limited to a very few applications such as technical filters, bank notes, bible paper, dielectric and medical paper, and cigarette paper, due to the high price of hemp pulp (Yu et al. 2017). Specialty papers also include teabag paper, coffee filter, speciality non wovens, greaseproof papers, carbon tissues and condensing tissues. Currently, the only well established market for hemp pulp is the cigarette paper market (European Industrial Hemp Association). Noteworthyy, in the production of cigarette paper, all the fiber in the stem can be used.

Nowadays, industrial hemp is not competitive on the paper market for the production of conventional papers, because the market is cyclical. For instance, kenaf has many economic advantages over hemp as non-wood fiber for the paper industry. Perhaps, the growing market for recycled pulp and paper may increase the demand for agricultural fibers to strengthen recycled papers. Similar to textiles, hemp fibers can be used as blends with other pulp fibers such as wheat straw or flax or even recycled wood, in order to increase paper performance, strength and recyclability. In addition, core and whole stalk are proposed to make lower end paper products, depending on available pulping technology that is tooled to process hemp efficiently. These markets can grow (Danielewicz and Surma-Slusarska 2017; Przybysz Buzala et al. 2017; Yu et al. 2017; Bajpai 2018).

Another promising market is filtration. Through comparison of oil filtration properties and air filtration properties with commonly used automobile engine oil/air cotton paper filtration materials, Feng and Zhang (2015) reported that hemp paper had the smaller thickness, weight, mean pore diameter, porosity and oil/air penetration, while the better oil/air filtration efficiency and higher pressure drop. Due to the higher filtration efficiency of hemp papers and green, biodegradable, sustainable resources of hemp plants in the case of environmental requirements, a pilot trial hemp paper automobile engine oil filter was successfully manufactured. The results indicated that hemp papers had better oil/air filtration properties than cotton paper in practical application.

2.3.3 Insulation and Building Materials

Compared to the traditional synthetic fiber materials, natural fibers such as hemp fibers represent a sustainable solution to be used for different applications in building construction, mainly because of their hygrothermal properties. Hemp-based materials can be manufactured into a variety of commercial products of various densities that resemble concrete, wood, and even plastic. In addition to the environmental value of using plant matter, these materials benefit from the mechanical strength of the hemp fibers.

Bio-based materials containing hemp also offer many other advantages over more established mineral and oil-based alternatives. These building materials are durable, light weight, affordable to produce, water-proof, fire-proof, self-insulating, resistant to mold, moisture-proof, highly breathable, and resistant to pests, and they have good heat resistance in winter time and cool in summer. The materials are also ideal for resisting damage caused by earthquakes, floods or other natural disasters (Shahzad 2012).

It is also claimed that hemp building materials trap carbon dioxide, making their use attractive from an environmental perspective (Zabalza Bribián et al. 2011; Ip and Miller 2012; Amziane and Arnaud 2013; Collet et al. 2013; Dubois et al. 2014; Latif et al. 2015; Jami et al. 2016, 2019; Jiang et al. 2018; Miller 2018; Moujalled et al. 2018; Pittau et al. 2018). However, the main disadvantage is the lack of guarantees in terms of durability (Walker et al. 2014; Arizzi et al. 2016).

As industrial products available on the market, hemp-based materials are subject to a number of National and European technical regulations and have been approved officially for use in the construction industry. Hemp fibers are mainly used for insulation, e.g. insulating material and insulation wool, and/or construction. Insulation is the second important application for hemp fibers today (European Industrial Hemp Association). These fibers can also be used for acoustic and soundproofing purposes. This is an area of research that is currently in full expansion.

With the exception of hemp seed, which has no significant use as a building material, hemp straw can provide two products/co-products for the construction industry: (1) the bast fibers and (2) the woody core of the stalk used to produce hurds. Due to their different properties, these two products are used to produce different construction and insulation materials (Figs. 2.5 and 2.6).

The materials can be made from the compressed inner short hemp fiber. The outer hemp fibers can also be used like straw in bale construction paired with mud for an old-style cob building. Hemp boon, obtained after crushing hemp woody core of the stem, is useful for thermal insulation composite production due to their small-pored structure.

High-quality building blocks are produced by mixing a binder, e.g. lime, clay or cement, with non-fibrous hurds particles (Elfordy et al. 2008; Pretot et al. 2014; Walker and Pavía 2014; Walker et al. 2014; Kinnane et al. 2016; Gourlay et al. 2017; Jami et al. 2019). These materials are bio-composites referred to hemp concrete, hempcrete or hemp-lime (Fig. 2.6). Hemp shives in combination with lime is currently another increasing market for construction, e.g. stucco/plaster production, caulking.

Fig. 2.5 Hemp panel wallboards made from 100% fibers. (Source: G. Chanet, Eurochanvre, Arc-les-Gray, France)

Fig. 2.6 Hemp-based products for insulation or building. (Source: G. Chanet, Eurochanvre, Arc-les-Gray, France)

Hemp provides all sorts of building materials: blocks and bricks, slabs and paneling, wallboard (Fig. 2.5), fiberboard, roofing tiles, and insulation products (Fig. 2.6). Hurds/shives are used to produce light concretes and mortars for different end uses, e.g. wall construction, insulation, underfloor, etc.

Due to their low density, elasticity, permeability, and insulating properties, hurds are also used for production of particle boards (Elfordy et al. 2008; Bouloc 2013; Walker et al. 2014; Cigasova et al. 2015; Ingrao et al. 2015; Fangueiro and Rana 2016; George et al. 2016; Jonaitiene and Stuoge 2016; Kinnane et al. 2016; Niyigena et al. 2016; Fernea et al. 2017; Gourlay et al. 2017; Kiruthika 2017; Liuzzi et al. 2017; Mirski et al. 2017; Chernova et al. 2018; Kallakas et al. 2018; Nováková 2018; Pichardo et al. 2018; Usmani and Anas 2018).

These environmentally friendly building materials are suitable for the construction of houses (e.g. Chanvribat®, Béton Chanvre Tradical® France). Hemp-based materials can indeed replace wood and other materials used to build homes and other structures including foundations, underfloor, walls, shingles, paneling, pipes, and paint.

Houses can be made nearly 100% out of hemp materials: walls can be hemp wallboard (Fig. 2.5) or hemp cement for walls (Fig. 2.6); insulation can be made of hemp, e.g. hemp cement to insulate under the floor boards; hemp bricks and hemp plaster; pipes can be made out of hemp plastic; paint made with hemp oil; hemp carpet for interiors, and even a hemp roofing material.

Hemp concrete was developed in France in the 1990s as an alternative to wattle and daub for the restauration of historic building (Bouloc 2013), in particular with the works of Charles Rasetti on the restauration of a mediaval timber framed building, "*Maison de la Turque*" at Nogent-sur-Seine in 1987. At that time, other projects on the renovation of historical buildings based on hemp-lime use, e.g. in Versailles, were also developed (Canosmose®, IsoChanvre®, ChanvriBloc®). However, Charles Rasetti was the first to patent hempcrete in 1986, Canobiote® and Canamose® (International Hemp Association). Canamose® was a light-weight concrete made with hemp hurds and natural lime, which might be used for all types of non load-bearing masonry, and was perfectly suited to walls sectioned with wooden supports. Canobiote® was hemp hurds coated with mineral salts, which was an effective process for the insulation of wood-framed, closed lofts and floors intended for regular use.

Currently, hemp concrete/hempcrete is commonly used in Europe, e.g. in France (Fig. 2.7), England, Germany, Ireland, Belgium, Luxembourg and Switzerland, as a multifunctional ecological material for building applications. Hemp-lime construction had also been adopted in North America (Quebec), South Africa, Israel, Australia and New Zealand.

The advantages often cited are: excellent thermal insulation properties, low thermal conductivity, high hygrothermal efficiency, breathability, low environmental impact, e.g. in terms of emissions of green-house gases, interesting acoustical properties, and particular hygrothermal behavior enabling a natural moisture regulation (Arnaud and Gourlay 2012; Mazhoud et al. 2017; Aït Oumeziane et al. 2016).

Hemp-lime is also a cheap and low density material with associated low thermal conductivity depending on the density and moisture level, and it presents an interesting balance between low mass and heat storage capacity compared with classical insulation materials. It is considered as a sustainable, carbon negative and low embodied energy construction material (Zabalza Bribián et al. 2011; Latif et al. 2015; Bouloc 2013; Kinnane et al. 2016).

2.3.4 Composites and Plastic Alternatives

Hemp fibers are used not only for insulation but also for the production of composites in the automotive, furniture and fashion industries where synthetic fibers are replaced by hemp fiber. Indeed, bast fibers are desirable for composite/biocomposite production due to their length and strength while hurds, the byproducts of extracting the bast fibers from the stalk, are interesting for particle board and biodegradable plastic production.

Fig. 2.7 A half-timbered building in Normandie, France, dating from the early nineteenth century. The walls and slabs were renovated using differents solutions based on hemp concrete. (Source: with the kind courtesy of Florence Collet (Rennes, France) and Yacine Aït Oumeziane (Belfort, France))

Active research continues in these areas (Faruk et al. 2012; Shahzad 2012; Bono et al. 2015; Cigasova et al. 2015; Fernando et al. 2015; Pil et al. 2016; Ummartyotin and Pechyen 2016; Gallos et al. 2017; Lamberti and Sarkar 2017; Liu et al. 2017; Mirski et al. 2017; Nunes 2017; Nurazzi et al. 2017; Chernova et al. 2018; Karaduman et al. 2018; Musio et al. 2018; Sarasini and Fiore 2018; Sepe et al. 2018; Spierling et al. 2018; Usmani and Anas 2018; Väisänen et al. 2018).

In 1941, Henry Ford used hemp-based plastics to build car doors and fenders. He produced a prototype, the Hemp Body Car, that showed the great potential of hemp used in combination with plastic technology; indeed 70% of straw mixed with a plastic composite. Ford demonstrated the strength of the hemp composite by hitting the car with a club and leaving no trace in the bodywork, a scene immortalized by a famous photograph (The Collections of the Henry Ford).

Ford predicted that his prototype "would be lighter, sager and less expensive" (New York Times, February 2, 1941). However, at that time, the technology was never put into mass production (Small and Marcus 2002). The car also was to run on hemp-ethanol. Ford was a visionary.

Currently, industrial hemp presents great opportunity for supplying a sustainable and carbon positive source of plasticizing material and several hemp-based plastics or bioplastics are on the market, e.g. in the automotive sector. Hemp can be processed into different forms used in automotive interior and exterior applications, e.g. carmakers are currently using hemp composite inserts, trunks, head-liners, spare wheel covers, parcel trays etc. An important market is the press moulding market for interior applications: door panels and car boot trims, rear shelf and roof liner panels, dashboards, pillar trims, seat shells, under bodies and other applications.

The biocomposites and bioplastics are price competitive in high-quality interior concepts although hemp fibers are also in competition with flax, jute and kenaf fibers. They are also considered less expensive than fiberglass counterparts and show the favourable mechanical properties of rigidity and strength in combination with low density.

Another interesting advantage can be cited: The material does not splinter and leaves no edges which is an important characteristic especially in the case of automobile accidents. It is also claimed that hemp fiber reinforced plastics show energy and greenhouse gas savings in comparison with their fossil-based counterparts. After use, their incineration with energy recovery shows higher energy and emissions of greenhouse gases savings compared to an analysis from cradle-to factory gate.

The bioplastics containing hemp are, for example, used to replace synthetic polymers and copolymers such as polyacrylonitrile-butadiene-styrene in dashboards. These products are hemp fibers reinforced polypropylene compound and are designed for automotive structural parts by injection process. They are mainly used in the German automotive industry (e.g. BMW, Mercedes, Volkswagen Golf), followed by the French (e.g. Peugeot 308, Megane, DS7 Crossback) and Italian (e.g. Alfa Roméo Giulia) industries. An example is Refine® Hemp-PP for the inserts and top roll of the door panels in the Peugeot 308. Another example is NAFILean™ used as biocomposite in the dashboard of the Alfa Roméo Giulia.

Hemp fiber reinforced plastics are also used in the production of furniture or other consumer products such as briefcases, glasses and fashion accessories. Biocomposites are proposed for high-performance products like yachts, composite sink basin, sunglasses and ski goggles (HempEyeWear®), or trays for grinding discs. Shives are proposed for insulation of airline seats. A hemp-plastic resin, HempStone™, is proposed for use in musical instruments, loudspeakers, and furniture, e.g. tables and chairs.

Khattab and Dahman (2019) recently reported the production and recovery of poly (3-hydrobutyrate) from agro-industrial residues of hemp hurd biomass, to prepare ecological bioplastics with low environmental impact. Their technology focused on converting wastes into useful biomaterials such as poly(3-hydrobutyrate), contributing to reduce the environmental footprint, through the concept of circular economy. Poly(3-hydrobutyrate) is a biodegrable and biocompatible material which stands out as replacement for fossil-derived plastics. However, much work is still needed to reduce the cost of this environmentally friendly biodegradable plastic. This polymer is also proposed for absorbable sutures, scaffolds, heart valves, and cardiovascular tissue supports. This research can lead to new markets.

2.3.5 Uses of Hemp for Domestic Animals

As already mentioned, fiber processing yields a significant quantity of hurds, corresponding to some 60% of the weight of the plant. Hurds are often considered as a byproduct with no worth (Small and Marcus 2002; Gibson 2006; Fike 2016). Indeed, they have a high bulk to price ratio, even when compressed, and cannot be economically transported very far. Today, special uses such as animal bedding and horticulture have become widespread and popular.

Due to its hydrophilic properties and its ability to absorb water, a valuable market for hurds is indeed in high quality bedding for horses, poultry and pet litter (Small and Marcus 2002). The hurds are more absorbent than straw, about four fold, and need to be changed less often. They have better odor suppressing abilities and are less allergenic than alternatives such as wood shavings, straw and hay. In addition, hemp, once on the ground, provides a stable surface that does not tend to move or slip. It is comfortable for horses, for it made up of small particles. However, the bedding is likely to ingested if the horses are hungry.

Cat litter made from granules of hemp powder absorbs urine and faeces and is particularly good at capturing odors. Cleaning of the litter tray is easy as the granules compact down after becoming soiled. They can then be used as a fertilizer of composted down. Hemp straw is used in cattle sheds as an alternative to barley or wheat straw. Small pieces of hurds are suitable as bedding for small mammals, e.g. hamsters, guinea pigs, chinchillas, mice, rats, and pigeons, as well as rabbits and snakes (Small and Marcus 2002; Bouloc 2013; Fike 2016; Johnson 2018).

2.3.6 Horticulture and Market Gardening

Hemp hurds are also used for horticultural mulch. Hemp mulch, like traditional mulch, is primarily used as a surface application for gardens that include vegetable, flower and even container plants such as shrubs. Hemp mulch is easy to handle and is not prone to caking on the surface. It does an excellent job of maintaining soil moisture, minimizing erosion, and suppressing weed growth and seed germination. Indeed, it eliminates the need for manual or chemical weeding control and act as a screen to keep seeds from germinating. Its water absorption capacity cuts down on the need for watering, as the shives keep the ground damper for longer. Hemp mulch is superior in insulating the soil from the hot sun and cold winter, especially frost protection. Product is also pH neutral, compatible with the pH of the soils, fully biodegradable and add humus to soils, i.e. as it decomposes, it helps to enrich the soil (Bouloc 2013; Cherney and Small 2016; Chandra et al. 2017).

Several manufacturers also offer hemp-based fleeces in the form of felt or mulch cloth, supplied mostly in rolls, e.g. Geochanvre® products, France. These materials are a biodegradable layer of fibers used to create a suitable planting environment that warms the soil, retains moisture, and deters weeds. It is also an ecological protection and an alternative to the use of herbicides. Figure 2.8 shows hemp-based products in felt form used in horticulture. They are considered as agricultural textiles or geotextiles (Small and Marcus 2002). For potted plants, they are also used for plant propagation and as a substrate (Kolodziejczyk et al. 2012; Jonaitiene and Stuoge 2016).

Fig. 2.8 Hemp-based products in felt form used in horticulture. (Source: G. Chanet, Eurochanvre, Arc-les-Gray, France)

Used as mulch mats for green areas, e.g. along highways or on roadsides against weed invasion, these biodegradable felts constitute an effective and environment-friendly alternative to plastic mulching. The plants are inserted through the mat, which promotes rapid growth. Once established, the constituent parts of the felt degrade, leaving natural organic matter for continued protection. Hemp fleeces can also be used in earthworks and water engineering, for example, to protect from erosion or to divide soil layers. These products show high saving potentials in terms of energy and emissions of greenhouse gases compared to polypropylene fleece (Kolodziejczyk et al. 2012; Fike 2016; Jonaitiene and Stuoge 2016; Johnson 2018)

2.4 Hemp Products in Animal Nutrition and Food Industry

Hemp seed is a valuable food for both human and animals. Since the 1990s, in several developed countries such as Canada, U.S, France, U.K. and Germany, the seed is gradually making a comeback as ingredients in food products, beverages or as nutritional supplements (Callaway 2004; Kolodziejczyk et al. 2012; Leson 2013; Russo and Reggiani 2013; Girgih et al. 2014c; The and Birch 2014; Bono et al. 2015; Dunford 2015; Andre et al. 2016; Fike 2016; Hartsel et al. 2016; The et al. 2016; Mikulcová et al. 2017; Pihlanto et al. 2017; Frassinetti et al. 2018; Jonhson 2018; Devi and Khanam 2019a, b; Fiorini et al. 2019; Mamone et al. 2019; Wang and Xiong 2019). Currently, there are a worldwide interest in health-promoting functional foods and dietary supplements. France is the world leader in hemp seed production (European Seed Certification Agencies Association, www.escaa.org).

Fig. 2.9 Hemp-based foods and beverages. (Source: G. Crini, Chrono-environnement, Besançon, France)

The renewal of hemp-based foods was due to the fact, in the 1990s, greater attention was paid to the nutritional composition of hemp seeds, particularly of their fatty acid spectrum, which have been found to have a unique and probably beneficial balance of so-called omega-3 and omega-6 fatty acids for health.

Other reasons can also be mentioned such as the growing interest in the valorization of agro-food byproducts, the search of new sources of proteins, the production of bioproducts, e.g. bioactive peptides, natural antioxidants and new natural beverages (Fig. 2.9), and different concerns such as food allergies, animal welfare, and the negative impact on the environment associated with animal-derived proteins (Pihlanto et al. 2017).

For instance, bioactivities claimed in numerous publications are antioxidative, antihypertensive, antimicrobial, anticholesterolemic, and also antitumoral activities, which have attracted growing attention not only from scientists but also from the food industry and consumers. However, more studies need to be done on these health benefits (Girgih et al. 2014a, b; Pihlanto et al. 2017).

Most hemp seeds are used as whole seeds, followed by hemp seeds for oil and dehulled seeds. The whole seed, the cheapest and less processed product, is mainly used for animal feed. In contrast, the dehulled hemp seed, first produced in quantity in Europe, is mainly used for human food (Small and Marcus 2002). The most expensive product, hemp oil, is almost entirely used for human food and cosmetics.

2.4.1 Hemp as a Source of Feed Additives

Currently, hemp is a feedstuff for animal diets (Bouloc 2013; Leson 2013; Fike 2016; Johnson 2018). Four main essentially different types of materials derived from the plant may be used: hemp seed, hemp seed cake/meal, hemp seed oil and whole plant. Further products such as hemp flour and protein isolate from seeds can also be used.

Seed and seed cake are particularly interesting as feed materials for all animal species, i.e. birds, ruminants, pigs, horses, poultry, pigeons, fishes (Bouloc 2013). Birds and fish feed are the main market for hemp seeds in animal feed. Seeds play an important role in the animal nutrition, providing mineral nutrients, vitamins, dietary fibers, as well as biologically-active compounds. Hemp seeds are also used by anglers as bait. The whole plant, including stalk and leaves, is also used for ruminants and horses. Cannabinoid-based formulations containing protein powders such as EliXinol™ are available as dogs treats.

Given the high value of the oils, future use of products in animal feeds may nevertheless be limited to the byproducts produced after the oils have been extruded (Leson 2013; Fike 2016). Indeed, the production of plant seed oils generates tons of processing wastes called seed cakes. These byproducts are then further processed into animal feed due to their high protein and energy contents.

In the last decade, the potential of hemp as an animal feed is dwarfed by its value to the foods, supplements, nutraceuticals, and cosmetics industries that create products and biologically-active compounds with expected health and diseases-prevention benefits for human use, nutrition or consumption. These markets are more lucrative (Johnson 2018).

2.4.2 Hemp Seed and Essential Oils as a Source of Human Food Additives

All hemp food products originate from hemp seeds, i.e. seeds themselves and its products such as meal, flour and protein powder, oil and bioactives substances (Callaway 2004). All these products are achieving a growing popularity in human nutrition as an important food resource (Andre et al. 2016; Frassinetti et al. 2018), the principal product made from hemp seeds today being undoubtedly the seed oil (Johnson 2018).

Demands for natural foods, functional foods, plant-derived proteins, gluten-free products, and bioproducts in worldwide markets have been a major driver of hemp production (Fike 2016). Growth in this market is not surprising given that hemp seeds have excellent fatty acid profiles and protein qualities, and have been used for centuries to treat various disorders (Leson 2013).

In the last years, an increasing use of hemp seeds was observed, due to their nutritional and beneficial properties among people interested in improving and maintaining their health status by changing dietary habits (Fike 2016; Pihlanto et al. 2017; Frassinetti et al. 2018; King 2019). Indeed, they play an important role in the human diet and are an excellent source of nutrients, containing all essential amino acids and fatty acids in sufficient amount and ratio to satisfy the dietary human demand.

Hemp seeds contain more than 30% of oil, i.e. 320–380 g/kg oil, 80% of which is polyunsaturated fatty acids (Callaway 2004; Rodriguez-Leyva and Pierce 2010; Russo and Reggiani 2013; The and Birch 2014; The et al. 2016; Pihlanto et al. 2017).

The oil as functional food is an exceptionally rich source of the two essential fatty acids, linoleic acid or omega-6 and alpha-linolenic acid or omega-3. The omega-6 to omega-3 ratio in hemp seed oil is between 2:1 and 3:1, which is considered to be optimal for human health. A 2.5 value is found in Mediterranean and Japanese diets where the incidence of heart diseases has been historically low (Russo and Reggiani 2013).

The metabolites of the two essential fatty acids, i.e. gamma-linolenic acid and stearidonic acid, are also present in oil. Hemp currently is the only known natural source of gamma-linolenic acid, a widely consumed supplement with numerous health benefits., e.g. to treat eczema and mastalgia.

A nut also contains 25–35% of lipids, 20–30% of carbohydrates, 10–15% of insoluble dietary fibers, and 20–25% of proteins with considerable amounts of vitamins, e.g. vitamin E (90 mg/100 g) and a rich array of minerals such as phosphorus, potassium, magnesium, sulfur, calcium, iron, and zinc (Callaway 2004; Rodriguez-Leyva and Pierce 2010). The seed, and thus oil, does not contain THC. Hemp seed are rich in proteins and contains absolutely no cholesterol. The two main proteins are globulin/edestin (60–80% of the total protein content) and albumin and both of the proteins are easily digested in the human gastrointestinal tract (Malomo and Aluko 2015a; Pihlanto et al. 2017).

Hemp seed protein is considered as a useful food ingredient and a suitable alternative source of functional proteins to traditional ingredients. However, there is scanty information on the structural and functional properties of the seed globulin and albumin fractions. Hemp seeds also contain nutritionally significant amounts of all essential amino acids, especially high levels of the amino acid arginine.

For all these reasons, hempseed oil is marketed as a nutritional additive and a health-promoting product. Oil from hemp seeds is far more valuable in terms of concentrated nutrients and proteins than soybean the nearest vegan alternative.

To retain its valuable constituents, hemp seed oil must be un-refined and cold pressed from non-heat treated seed. Before treatment, hemp seed oils are off-yellow to dark green color. Purified or refined, oil is clear and colorless and has a pleasant, nutty taste/flavor. It is a versatile product, used in liquid or capsule form (oil gel caps). It is best consumed raw, in salad dressings or as a garnish or mayonnaise, and it can be poured over pasta to give extra flavor. Indeed, due to its precious fragile essential fatty acids, it is better not to cook it, e.g. this can create toxic trans-fatty acids. Unsaturated oils also oxidize very easily, which is why such oil quickly becomes rancid on exposure to the air. Hemp seed oil is fairly unstable and becomes rancid rather quickly unless preserved.

Other products being produced today include hemp sauce, butter, hemp meal and gluten-free flour, protein powders (EliXinol™), pasta and spaghetti, sorghum and hemp cakes (Fiorentini®), snack foods, energy bars, hulled hemp seed, muesli, toasted hemp seeds, burger mix, crackers (FoodsAlive©), pancakes, porridge, fruit crumble, chocolate (Fig. 2.8), sweets (Plus™), sour hemp gum, frozen dessert and ice cream (SanMarco®), hemp cheese, etc. Hemp seeds are also incorporated into pizza or used as salt substitute.

Consumers are increasingly looking for products which are not only diverse in terms of taste, but also demonstrate improved nutritional properties, selecting foods with specific health-promoting properties (Fathordoobady et al. 2019; Mikulec et al. 2019). Over the recent years, it has become very popular to enrich food products, including bread, with functional additives.

Mikulec et al. (2019) recently reported hemp flour as a valuable component for enriching physicochemical and antioxidant properties of wheat bread. The aim of their study was to use hemp flour for the production of bread and to determine their impact on selected chemical, texture, organoleptic characteristics, the color of the crumb, changes in the crumb texture, polyphenol profile, the total polyphenol and furan derivatives content. There is a lack of data regarding the influence of hemp flour on the antioxidant potential of bread nor the formation of furan derivates.

The results showed that bread with hemp flour was characterized by significantly higher protein content, in comparison to wheat bread. The share of 30 and 50% of hemp flour contributed to the reduction of organoleptic assessment of the bread. The hemp flour content significantly inhibited the changes in the hardness of bread crumb by reducing bread stalling index from 1.12 (wheat bread) to 0.05 (50% of the additive). The share of hemp flour influenced the color of the crumb by increasing its browning index from 29.69 (standard bread) to 46.26 (50% of the additive). The share of hemp flour influenced the polyphenols content and the formation of furan derivatives, e.g. furfuryl alcohol, furfuryl aldehyde and hydroxymethylfurfural, was dependent on the participation of hemp flour. For industrial production, the share of hemp flour should not exceed 30% (Mikulec et al. 2019).

Hemp protein powder is brownish-green in color and has a taste that can be described as earthy or grassy for some, or nutty for others. It can have a grittier texture than other plant-based protein powders. So, it is best consumed blended with other ingredients (Small and Marcus 2002). For example, hemp powder is added to shakes or smoothies to boost protein intake. The cold-pressed hemp proteins are digestible. Protein powders containing essential amino acids, fibers, unsaturated fats, minerals, e.g. magnesium and iron, and antioxidants are popular nutritional supplements used by vegan persons, athletes, and bodybuilders to increase muscle mass (Bouloc 2013; Cherney and Small 2016; Fike 2016; Chandra et al. 2017; Johnson 2018).

However, there is a debate in the literature on the exact amount of the essential amino acids present in hemp protein powder and on their real impact. In addition, while hemp protein powder is safe for most people, there can be potential side effects, e.g. it can cause digestive problems. It is not recommended for pregnant or lactating women, and people with anemia or with allergies (Cherney and Small 2016; Chandra et al. 2017).

From a fundamental research point of view, there are a considerable effort to improve both nutritional and functional properties of hemp proteins through the exploitation of innovative processing conditions (Malomo et al. 2014; Malomo and Aluko 2015a, 2015b; Korus et al. 2017; Pihlanto et al. 2017; Hadnađev et al. 2018; Dapčević-Hadnađev et al. 2019; Fathordoobady et al. 2019; King 2019; Wang and Xiong 2019; Zajac et al. 2019).

A technological challenge is the incorporation of hemp proteins, both as technological and biofunctional agents, into food products. Indeed, the utilization of these proteins in foods is limited because their behaviour highly depend on their structure and composition, environmental factors, e.g. pH, ionic strength, type of salt used, temperature, and isolation technique (Yin et al. 2008, 2009; Malomo and Aluko 2015a).

Various technologies have recently been proposed to improve the properties of hemp proteins, in particular gelling, foaming, and emulsifying properties, and antioxidant activity (Pihlanto et al. 2017; Hadnađev et al. 2018; Dapčević-Hadnađev et al. 2019; Zajac et al. (2019).

Zajac et al. (2019) recently reported that hemp products as valuable sources of nutrients such as fatty acids, proteins and minerals, could be used to create functional meat products. This topic is interesting since the research on meat products containing hemp ingredients is limited. The authors compared the quality of pork loaves produced with the addition of hemp seeds (5%), de-hulled hemp seeds (5%), hemp flour (5%), and hemp protein (5%).

The results showed that addition of hemp ingredients increased the products' hardness and the fibre content. Magnesium, manganese, iron and copper content was also higher in the products with hemp. Polyunsaturated fatty acids content increased in products with de-hulled and whole hemp seeds. Oxidation is decreased in products with hemp ingredients containing hemp shell. There was no change in the microbial growth after the addition of all the tested ingredients.

The overall acceptability was lower for the products with hemp ingredients, but the taste of meat loaf with de-hulled hemp seeds was comparable with the control product. Zajac et al. (2019) concluded that the most promising ingredients in terms of improving the products' nutritional value were hemp seed and de-hulled hemp seed.

It was possible to create functional meat products using hemp ingredients, with the suggestion to make an optimal mixture, to increase the content of nutritional components without decreasing the consumers' acceptance. However, to encourage the consumers to consume hemp enriched meat products, the information about the healthy ingredients should be provided (Zajac et al. 2019).

Although most research has focused on hemp seeds as a source of oils, proteins and essential fatty acids and minerals, recent studies also showed that that hemp inflorescences from fiber plants, i.e. hemp flowers and upper leaves, could be a good source of essential oils for flavoring in foods. However, the economic potential of these oils remains undefined (Fike 2016; Johnson 2018).

2.4.3 Nutraceutical Potential of Hemp Seeds and Sprouts

Hemp-based foods are gaining popularity and the nutraceutical domain is developing fast due to several factors like the change of lifestyle, interest in alternative diets, and the increasing wareness about sustainable production of food.

Hemp seeds and oil are particularly interesting the nutraceutical domain because they are also an excellent source of protein, minerals, dietary fibre, essential fatty acids, amino acids, and other bioactive substances such as polyphenols. Polyphenols as antioxidants can protect the organism against free radicals attack by reducing or inhibiting cell damages due to the oxidation of lipids or other biomolecules (Conrad 1997; Hartsel et al. 2016; Frassinetti et al. 2018). However, the nutraceutical domain is in its infancy and needs to progress. In addition, food-grade hemp seed requires detailed functional characterization of component proteins (Malomo and Aluko 2015a).

Frassinetti et al. (2018) recently reported that seeds and sprouts of *Cannabis sativa* were rich in phytochemical compounds, particularly polyphenols such as caffeoyltyramine and cannabisin A, B, and C, and also in amino-acids and saccharides. They possessed *in vitro* and *ex vivo* antioxidant activity, and also anti-mutagenic activity on yeast *Saccharomyces cerevisiae*. Due to the presence of bioactive compounds, seeds and sprouts can be used for nutraceutical and/or therapeutic purposes.

The et al. (2016) and Girgih et al. (2014a) previously reported the antioxidant and anti-hypertensive properties of hemp seed peptides and protein hydrolysate. Werz et al. (2014) also suggested the use of hemp sprouts as a novel anti-inflammatory hemp food product finding that germination and sprouting processes induced the production of anti-inflammatory compounds, prenylflavonoids cannflavins A and B, while cannabinoids were not present at sprout stage.

The byproducts of the oil production also contain secondary metabolites namely phenolic acids and flavonoids that have not been studied extensively. The and Birch (2014) showed that the application of ultrasound for optimization of yield of polyphenols from seed cakes contributed to industrial applications economically and environmentally since it reduced the usage of organic solvent and extraction time. The application of this technique was able to increase polyphenol extraction yields from cakes and aided in enhancing antioxidant capacity of the extracts.

The incorporation of heat during ultrasonic extraction resulted in higher polyphenol yields from the seed cakes compared to the ultrasonic treatment without heat. The polyphenols extracted from the seed cakes by ultrasonic treatment were a good source in product development for nutraceuticals and functional foods that could extend product shelf-life.

2.4.4 Hemp and Beverages

In the last decade, plant-based foods and beverages are gaining popularity and the market is developing fast (Chalupa-Krebzdak et al. 2018; Jeske et al. 2018; Jørgensen et al. 2019). For instance, there has been an expansion of milk alternative beverages originating from plant-based sources including soy, coconut, nuts, and hemp, e.g. Bjorg®, Evernat® and Pacific™ Foods. The reasons for the emergence of market for milk substitutes of plant origin could be attributed to several factors such as cow's milk intolerance, e.g. lactose intolerance, cow's milk allergy, e.g. milk protein allergies, cultural reasons or diet choice, e.g. veganism, flexitarian diet, etc.

Among the various products on the market, hemp seed milk is a popular vegetable alternative to cow's milk, e.g. it is beneficial for people who are lactose intolerant or who avoid dairy products, soy or gluten (Small and Marcus 2002). It is also a good choice for those on a vegan diet. Hemp milk can easily be created at home by mixing water with the seed. This milk is rich in high-quality plant protein, healthy fats and minerals. The hemp-based milk alternative has a protein content of 0.83 g 100 mL^{-1}. This hemp milk also contains alpha-linoleic acid, an essential omega-3 fatty acid, at 0.4 g 100 mL^{-1}, i.e. 25% of recommendend 1.6 g day^{-1} intake (Chalupa-Krebzdak et al. 2018). Some commercial varieties are also fortified with vitamins and minerals.

Compared to whole cow's milk, hemp milk has fewer calories, less protein and carbs but roughly the same amount of fat. It has an earthy, nutty flavor and a creamy consistency. It can be used in place of cow's milk in smoothies, coffee or cereal. Indeed, due to its creamy consistency and protein content, hemp milk is excellent for making lattes, cappuccinos and other coffed drinks. A major concern people have about hemp milk is that it may contain THC as ingredient which is not the case from a regulatory point of view (Bouloc 2013; Jonaitiene and Stuoge 2016; Chandra et al. 2017; Johnson 2018).

Hemp is steadily creeping into a wide range of beverage products (Fig. 2.9), e.g. protein shakes, infusions, hemp-infused beers, e.g. Turn®, Cannabia®, Mandrin®, Coors Light®, and Appenzeller Hanfblüte™, hemp-infused wines, hemp cocktails, e.g. Hempfy tonic gin, alcohols (hempseed used as a flavorant), e.g. Hempfy Martini, lemonades, tea, e.g. HempTea, and coffee nog. Hemp seeds can also be used in a smoothie or a yogurt. All these products have a niche market, based on natural food and beverages, and specialty food outlets.

2.5 Hemp for Cosmetics and Hygiene

All the advantages associated with hemp give hemp seed oils a high market value and make their use likely not only in human food and nutritional supplements, but also in cosmetology and skin care (Fig. 2.10), aromatherapy, and medicine (Conrad 1997; Small and Marcus 2002; Bertoli et al. 2010; Kolodziejczyk et al. 2012; Ionescu et al. 2015; Ligeza et al. 2016; Bonini et al. 2018).

Fig. 2.10 Hemp-based cosmetics. (Source: G. Crini, Chrono-environnement, Besançon, France)

Hemp oil is indeed a good alternative to the chemicals present in many petroleum-based lotions and cosmetics. It is widely used in wellness and body care stores, e.g. for skin hydratation, hand protector, hand sanitizer, body butter, body wash, etc. Its use is intented for people who are both sensitive to their well-being and to the protection of the environment. Consumers have a preference for natural ingredients with little or no impact on the environment.

In cosmetology, hemp is considered as a valuable resource for green cosmetics due to the high content of oil containing interesting substances for skin care with technological and therapeutic effects (Small and Marcus 2002; Vogl et al. 2004). In particular, hemp oils are interesting as natural ingredients/additives due to their high concentration of fatty acids, minerals and vitamins. Fatty acids are structural compounds of phospholipids in cell membranes that influence several cell membrane functions such as hormone activity.

Hemp oils and extracts have also captured a special attention due to their high antioxidant potential (Ionescu et al. 2015; Ligeza et al. 2016). Soothing and restructuring, natural cold pressed oils can be applied to the skin, on the face and on the body (Conrad 1997). Thanks to its natural emollient and moisturizing properties, hemp oil is a common ingredient in body care products, e.g. soaps, shampoos, creams (SATIVA™, BodyShop®), lotions, conditioners, and many other hair and beauty products, e.g. hair care, hair hydration and nourishment, scrubs, perfumes (Cannavis Santal Eau de Parfum), sunless bronzers (HEMPZ®), lipstick (HempOrganics™), etc. The commercial products are paraben-free, THC-free, and 100% vegan. Recent studies claim that oil reduces wrinkles and keeps the skin a youthful appearance (Ionescu et al. 2015; Ligeza et al. 2016).

The inflorescences of industrial hemp, obtained during cultivation, represent a consistent byproduct that is underutilized. Its great availability make it a potential additional resource to exploit and valorize at industrial level to produce niche products not only for food industry flavoring in foods, but also for cosmetics and pharmacy industry.

Indeed, hemp flowers and upper leaves contain essential oils that they can be used as a scent in perfumes, soaps and candles (Bertoli et al. 2010). These essential oils also have interesting antimicrobial and insecticidal activities (Górski et al. 2009). They can also be used in medicinal formulations (Fernandez-Ruiz et al. 2013). However, research on these topics is still poor (Benelli et al. 2018).

Cosmetic, functional foods and nutraceutical markets appear to be currently driving the hemp revival. However, products remains relatively expensive and their consumption is likely to be restricted.

2.6 Hemp in Medicine

Just as hemp has been used for centuries for domestic and industrial purposes, hemp and cannabis/marijuana have been used for almost as long for medicinal purposes. Hemp seeds and its oil have been used to treat various disorders for thousands of years in traditional Asian medicine (Conrad 1997; de Padua et al. 1999; Leson 2013; Richard and Dejean 2013; Bonini et al. 2018). The medicinal properties of hemp have been exploited since 5000 BC in China and India, e.g. for a number of indications including fever, rheumatic pains, menstrual pains and constipation. The Ancient Greeks and Romans also used cannabis roots for medicinal purposes. For a historical review of this topic, see Russo (2007) and Hanus (2009).

As we have already said, hemp/industrial hemp and marijuana/medical cannabis are often confused (Holler et al. 2008; Sawler et al. 2015; VanDolah et al. 2019). However, hemp and marijuana are different varieties of the plant *Cannabis sativa* L., the first being grown for seeds, oil, fibre and therapeutic hemp, the second for its high content of the psychoactive substance tetrahydrocannabinol (cannabidiol oils).

Industrial hemp versus therapeutic hemp? Hemp is grown differently than marijuana, and the extract is obtained from specific parts of the plant which do not contain tetrahydrocannabinol. Most of the tetrahydrocannabinol content is found in the buds and flowers of the cannabis plant, but industrial hemp is not cultivated to produce buds, so this explains the different content of tetrahydrocannabinol in marijuana versus hemp.

What is therapeutic hemp? This term refers to strains of cannabis that do not contain enough tetrahydrocannabinol to render a psychoactive reaction when ingested by the user. Therapeutic hemp is used to make cannabis concentrate oils that are high in cannabidiol rather than tetrahydrocannabinol. The oil derived from therapeutic hemp is commonly referred to as cannabidiol hemp oil. Charlotte's Web Medical Hemp Act defines therapeutic hemp as "hemp that doesn't make you high".

VanDolah et al. (2019) recently summarized the current legal status of cannabidiol and hemp oils in the United States and provided a guide to identifying higher-quality products so that clinicians could advise their patients on the safest and most evidence-based formulations.

Hemp seeds are a good source of cannabidiol but special extraction techniques are required for its production. From the 1970s, the pharmaceutical industry developed various cannabinoid-based formulations, e.g. Cesamet©, a synthetic derivative of tetrahydrocannabinol used to treat vomiting and nausea and against neurological pain (Small and Marcus 2002), Marinol© also used in the treatment of nausea and vomiting and it can stimulate the appetite of cachectic AIDS patients (Richard and Dejean 2013).

Essential oils containing cannabinoids are approved and marketed, e.g. Sativex® Nabiximol as adjunctive treatment for symptomatic relief of spasticity in adult patients. These products are indicated for the treatment of multiple sclerosis, epilepsy and side effects of cancer chemotherapy. In 2018, the first cannabidiol-based drug, Epidiolex®, was approved by the US Food and Drug Administration for treatment of rare, severe epilepsy, further putting the spotlight on cannabidiol and hemp oils (VanDolah et al. 2019).

Currently, in China, hemp is widely used as a component not only for food but also for medicine: medicines that heal wounds, temper chronic pain, rheumatic pains, menstrual pains and nausea, reduces seizures in epileptics, to reduce acne breakouts and improve skin conditions, to treat dermatitis and eczema, etc.

There are other benefits attributed to compounds derived from various parts of the hemp plant, particularly seed due to its polyunsaturated fatty acids and cannabidiol content, such as anticancer, anti-inflammatory and anti-thrombosis properties, stimulation of general metabolism, neuroprotective effect, promotion of fat burning, hypertension and oxidative stress treatments, help to regulate the immune system, and inflammatory bowel disease (Rodriguez-Leyva and Pierce 2010; Cassano et al. 2013; Russo and Reggiani 2013; Girgih 2014a, b; Cherney and Small 2016; Hartsel et al. 2016; Parian and Limketkai 2016; Pathak et al. 2016; Bonini et al. 2018; Zhou et al. 2018; Devi and Khanam 2019a; Fathordoobady et al. 2019; Fiorini et al. 2019; Mamone et al. 2019).

Some research has suggested that hemp seeds could protect the brain, e.g. positive effects in Parkinson's disease, Alzeimer's disease, and multiple sclerosis (Sativex® is approved in Canada), boost heart health, e.g. reduce the risk of arrhythmias, reduce inflammation (type 2 diabetes), relieve rheumatoid arthritis, and improve skin conditions, e.g. reduce acne symptoms (Rodriguez-Leyva and Pierce 2010; Cassano et al. 2013; Russo and Reggiani 2013; Girgih 2014a, b; Cherney and Small 2016; Hartsel et al. 2016; Parian and Limketkai 2016; Pathak et al. 2016; Bonini et al. 2018; Zhou et al. 2018; Devi and Khanam 2019a; Fathordoobady et al. 2019; Fiorini et al. 2019; Mamone et al. 2019).

However, although the properties and virtues of hemp have been recorded for several thousand years, their medical applications are still not universally recognized and continue to stir much controversy (Fike 2016; Żuk-Gołaszewska and Gołaszewski 2018). Much work is needed to verify various claims about hemp's efficacy.

As reported by Fike (2016) "excitement over this potential needs to be cautious because data in the literature regarding hemp's nutritional and medicinal benefits are somewhat limited and variable, and much of the work has been conducted with animal models". Indeed, great care must be continually taken when reading information on therapeutic hemp and wellness.

2.7 Essential Oils from Hemp as an Effective Tool for Insect Pest Management

Hemp flowers and upper leaves, considered as low-cost byproducts, contain essential oils that they can be used as flavoring in foods or as a scent in cosmetics (Thoma et al. 2000; Small and Marcus 2002). Interestingly, these oils have also been shown to be toxic mosquitoes larves (Thoma et al. 2000). Other valuable properties often cited are their antimicrobial (Verma et al. 2014) and nematicidal (Mukhtar et al. 2013) properties. Thus, byproducts of industrial hemp could also represent an exploitable material to produce biopesticides for agrochemistry sector.

The use of hemp in agrochemistry seems to be a promising field as reported in various studies (Mukhtar et al. 2013; Isman 2015; Bedini et al. 2016; Pavela and Benelli 2016; Abé et al. 2018; Benelli et al. 2018; Fiorini et al. 2019). The following example is interesting.

The Asian tiger mosquito *Aedes albopictus* is acknowledged as the most invasive mosquito species worldwide. Because of its aggressive daytime human-biting behavior and its ability to transmit many pathogens and parasites, including dengue yellow fever and chikungunya, it represents a key threat for millions of people worldwide. The freshwater pan-pulmonate snail *Physella acuta* is another problematic invasive species that shares the same habitats of the *Aedes albopictus* larvae and it is considered a plague in rice fields. Nowadays, pests are largely controlled by synthetic pesticides. However, the continuous use of organophosphates and insect growth regulators has caused the rising of resistant mosquito strains. Besides, currently employed molluscicides are limited in number, expensive and also have negative effects on human health and the environment. Thus, there is a growing interest for alternative eco-friendly control tools for pest management.

The potential of essential oil from industrial hemp as an environmental-friendly botanical insecticide was studied by Bedini et al. (2016). These authors reported that this essential oil was effective against larvae of mosquito vectors and moth pests, as well as against flies and snails. They concluded that hemp essential oils represented new low-cost environmentally friendly insecticides and molluscicides. In addition, these oils are interesting because they are characterized by low toxicity towards other non-target organisms.

Another recent work has been published by the same group (Benelli et al. 2018). The authors used an essential oil obtained by fresh inflorescences of hemp, monoecious *cv*. Felina 32 by steam-distillation. Its composition, analyzed by gas chromatography and gas chromatography-mass spectrometry, was dominated by monoterpene and sesquiterpene hydrocarbons, with (*E*)-caryophyllene (45.4%), myrcene (25.0%) and α-pinene (17.9%) as the most abundant derivatives. The oil was tested against the filariasis vector *Culex quinquefasciatus*, the peach-potato aphid *Myzus persicae*, the housefly *Musca domestica* and the tobacco cutworm *Spodoptera littoralis*. To prove its harmlessness on non-target invertebrates, it was also tested on the multicolored Asian lady beetle, *Harmonia axyridis*, and *Eisenia fetida* earthworms, and compared with α-cypermethrin as the positive control.

Results from insecticidal tests showed that the essential oil from inflorescences of industrial hemp *cv*. Felina 32 was highly toxic to *Myzus persicae* aphids (LC50 of 3.5 mL L^{-1}) and *Musca domestica* flies (43.3 μg $adult^{-1}$), while toxicity was moderate towards *Spodoptera littoralis* larvae (152.3 μg $larva^{-1}$), and scarce against *Culex quinquefasciatus* larvae (LC50 of 252.5 mL L^{-1}) and adults (LC50 > 500 μg cm^{-2}). Contrary to α-cypermethrin, the hemp *cv*. Felina 32 essential oil was not toxic to non-target invertebrate species, including third instar larvae and adults of *Harmonia axyridis* ladybugs and adults of *Eisenia fetida* earthworms. The authors concluded that the essential oil from industrial hemp byproducts is an effective tool for insect pest management in organic crops, particularly to manage aphid and housefly populations (Benelli et al. 2018). The chemical characterization is a crucial step before any kind of biological assay.

Abé et al. (2018) also reported the insecticidal activity of *Cannabis sativa* L. leaf essential oil on the malaria vector *Anopheles gambiae* s.l. larvae. Their work showed high insecticidal effect of this oil against both larvae and adult after 24 h of exposition in controlled conditions. The authors concluded that *Cannabis sativa* L. leaf essential oil could be a serious alternative to insecticides. Further studies are required to assess the same effect in the environment.

2.8 New Uses for Hemp in Energy Production

Industrial hemp is an attractive biomass not only for bioplastic production but also for energy production. Indeed, biomass conversion to biofuels and bioproducts has generated in the last three decades a lot of interest due to the increasing demand for producing a sustainable energy supply that can be incorporated to the existing fuel system.

Traditionally, biofuels have been produced based on starches or sugars such as wheat, corn, sugar beets and sugarcane. New opportunities to use hemp biomass as solid fuel or feedstock in biogas and bioethanol production have been reported. A number of claims have been made that hemp could be used in energy production, as a fuel source with no sulfur emissions, either burnt directly or converted into liquid fuels such as bioethanol (Burczyk et al. 2008; Rice 2008; Li et al. 2010; Sipos et al.

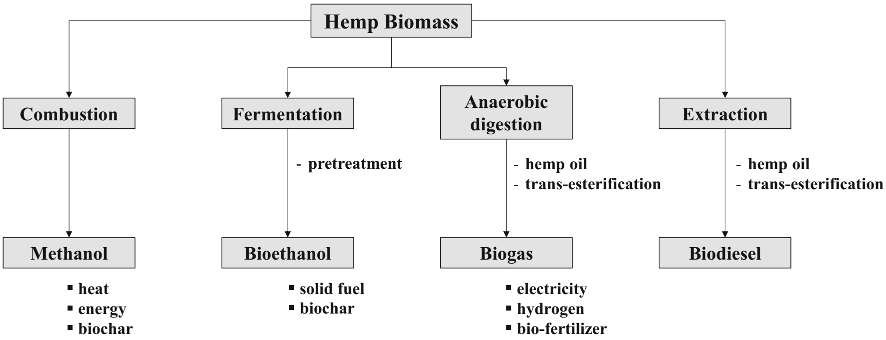

Fig. 2.11 Bioenergy pathways based on hemp biomass conversion. (Adapted from Rehman et al. 2013)

2010; Ahmad et al. 2011; Kreuger et al. 2011; Prade et al. 2011, 2012; Gomes 2012; Finnan and Styles 2013; Rehman et al. 2013; Kuglarz et al. 2014, 2016; Fernando et al. 2015; Das et al. 2017; Schluttenhofer and Yuan 2017).

Industrial hemp is valuable due to its high biomass and energy yields per hectare. For centuries, hemp oil was used as lamp oil. Today, hemp oil can be used to create biofuels to replace gasoline for diesel engines without any needed modifications. These biofuels are renewable and produce less of greenhouse gas carbon monoxide, potentially helping relieve global warming.

Figure 2.11 shows the possible pathway of bioenergy production from industrial hemp biomass (Rehman et al. 2013). This annual plant can be used to produce different products in a biorefinery concept which includes production of vehicle fuels, e.g. biogas from anaerobic digestion or bioethanol from fermentation, heat from briquettes or pellets, electricity from baled biomass, feed and biochemical such as succinic acid. Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and in crop rotations (annual cultivation). The main competitors for hemp are maize and sugar beets for biogas production and the perennial crops willow, reed canary grass and miscanthus for solid biofuel production (Prade et al. 2012).

Hemp can provide two types of fuels/biofuels, biodiesel made from the oil of the pressed seed and bioethanol and methanol made from the fermented stalk. Biodiesel is considered as a clean and renewable energy alternative to petroleum-based diesel fuel. Bioethanol is also considered as one of the most promising biofuels as it can be easily incorporated into existing fuel systems and can partially substitute fossil fuels used in transportation. However, the most important problem is to understand whether industrial hemp can yield biofuel quantities comparable to the other biomass feedstocks. Another problem is the development of efficient pretreatment technologies to remove lignin and facilitate enzyme access to the cellulose for sugar release.

Angelidaki's group demonstrated that industrial hemp can be used for cellulosic bioethanol and succinic acid production in a biorefinery concept (Kuglarz et al. 2014, 2016). Two types of pretreatments, i.e. dilute-acid treatment and alkaline oxidative method, were studied. The results showed that high cellulose recovery (>95%) as well as significant hemicelluloses solubilization (49–59%) after acid-based method and lignin solubilization (35–41%) after alkaline H_2O_2 method were obtained. The highest ethanol production was achieved after hemp pretreatment by alkaline oxidative method (Kuglarz et al. 2016). However, acid-based pretreatment of hemp was superior to alkaline oxidative method with respect to the combined ethanol and succinic acid production.

The mass balance calculations showed that 149 kg of bioethanol and 115 kg of succinic acid can be obtained per 1 ton of dry hemp. Taking into account the costs of biomass processing, from field to ethanol facility storage, the field-dried hemp pretreated at the optimal conditions showed positive economic results. Angelidaki's group previously showed that the type of hemp cultivation, i.e. organic or conventional, did not influence significantly the effectiveness of the pretreatment as well as subsequent enzymatic hydrolysis and ethanol fermentation (Kuglarz et al. 2014).

Das et al. (2017), using a combined agronomic, experimental and economic analysis approach, reported that industrial hemp is a potential bioenergy crop in comparison with kenaf, switchgrass and biomass sorghum. For instance, the authors reported a predicted ethanol yield of 82 gallons/dry ton hemp stems which was comparable to the other three tested feedstocks. However, despite numerous studies related to the biofuels potential of hemp, its technical and economic feasibility still remains unclear (Fike 2016; Johnson 2018).

2.9 Environmental Applications

One of the most interesting applications for hemp is in cleaning up soil contamination through phytoremediation and phytoextraction processes. Hemp has been tested with favorable results as phytoextractor in areas where lands were contaminated with various pollutants such as metals, radioactive elements, organics including pesticides and fertilizers, oils and solvents (Linger et al. 2002; Small and Marcus 2002; Citterio et al. 2003; Vandenhove and Van Hees 2003; Gomes 2012; Gupta et al. 2013; Ahmad et al. 2016; Morin-Crini et al. 2018; Saxena et al. 2020).

Linger et al. (2002) previously reported that hemp was able to decontaminate metal polluted soils. All parts of plants, i.e. seeds, leaves, fibers and hurds, contained metals but the metal accumulation in these different parts was extremely different. The highest concentrations of Ni, Pb and Cd were accumulated in the leaves. In the field trial, hemp demonstrated a phytoextraction potential of 126 g Cd (ha vegetation period)$^{-1}$. The authors showed that the high quality of the fibers and hurds, which were not affected by the metal contamination, allowed them to be used in special products like combine material (Linger et al. 2002).

Hemp plants were shown to be effective in cleaning the soil around the site of Russia's Chernobyl nuclear disaster (Vandenhove and Van Hees 2003). They were also considered for use near Fukushima (Morin-Crini et al. 2018).

Another interesting environmental field is the removal of pollutants present in aqueous solution by hemp-based biosorbents. Indeed, with the increasing focus on renewable materials and sustainability issues, the development of non-conventional materials from natural resources and possessing complexing and chelating properties such as hemp is currently an area of extensive research due to their potential applications in pollutant removal, e.g. in water and wastewater treatment.

This is an interesting challenge because the majority of commercial organic resins are derived from petroleum-based raw materials using processing chemistry that is not always safe or environmental friendly. Today, there is growing interest in developing natural low-cost alternatives to synthetic resins and polymers. Hemp as biosorbent could be a promising alternative.

In the last decade, several research groups published numerous works on the ability of hemp to act as an effective biosorbent for the removal of metals from aqueous solutions or industrial effluents (Kostić et al. 2008, 2010; Pejić et al. 2008, 2009, 2011; Rosas et al. 2009; Tofan et al. 2009, 2010a, b, c, 2013, 2015, 2016a, b; Zou et al. 2012; Vukčević et al. 2012, 2014a, b, 2015; Yang et al. 2011, 2012; Rezić 2013; Sun et al. 2013; Balintova et al. 2014; Lupul et al. 2015a, b; Kyzas et al. 2015; Wang et al. 2015; Bugnet et al. 2017a, b; Loiacono et al. 2017a, b, c, 2018a, b; Morin-Crini et al. 2018, 2019).

Many materials containing hemp in raw, modified or carbon forms, have been proposed. All these results clearly demonstrated that hemp had a high affinity for metals such as Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn. Hemp is able to remove metals from mono- and polycontaminated solutions and the performances are in general almost independent of pH between 4 and 6. Strong bonding of metal ions by carboxylic present in hemicelluloses, pectin and lignin, phenolic (lignin and extractives), carbonyl (lignin) and hydroxyl (polysaccharides) groups are responsible of the adsorption through chemisorption. However, the performance depends on the hemp form used, i.e. fibers, shives or felt, and also on the residual concentration of the metal in solution. In addition, all the works are in the stage of laboratory-scale study using often standard solutions containing one or a few metals. Future research needs to demonstrate the possibilities on an industrial scale using real polycontaminated wastewaters and discharge waters (Morin-Crini et al. 2018, 2019).

2.10 Miscellaneous Applications

Other domains for hemp uses include paints, e.g. Chanvre Mat, Milk Paint, varnishes, ink and lubricants, solvents, detergents, and industrial cleaners (Small and Marcus 2002; Callaway 2004; Bouloc 2013).

Innovative applications such as coatings, nanotechnology, e.g. nanomaterials with similar properties as graphene, supercapacitors (TitanHemp) and nanosheets, hemp plastic for 3D printing (Kanesis HBP®), biocomposites for airplanes or solar panels, in cleaning up air, acoustic domain and biotechnologies (Khattab and Dahman 2019; Rossi et al. 2020) opens new challenges. For instance, hemp-based supercapacitors offer an affordable next generation energy source to replace rechargeable batteries for applications such as electric cars, power tools and mobile devices (Sun et al. 2016). Several patents have been filed in recent years.

2.11 Conclusion

Industrial hemp is commonly used to refer to Cannabis strains cultivated for industrial use, i.e. for non-drug use. Although industrial hemp is a niche crop (Food and Agriculture Organization of the United Nations, www.faostat.fao.org), its production is currently experiencing a renaissance, particularly in Europe and North America. China is the largest producer and exporter of hemp in the world. Hemp is a valuable crop for the bio-based economy because of its unique properties and environmental benefits, and the high yield of natural products it provides.

Hemp is a multi-purpose crop delivering stalks, seeds and leaves, which find numerous applications. Its uses are indeed manifold: construction materials, textiles, paper, food and beverages, automotive sector, furniture, luxury market, cosmetics and personal care items, etc. There are an estimated 25,000 products derived from industrial hemp. The importance of functional foods and nutraceuticals containing hemp products is related to health promotion and diseases risk reduction. Neutraceutical products, cosmeceuticals, medical and therapeutic domains should be the next market in the development of industrial hemp. Other potential uses and innovative applications opens new challenges, e.g. phytoremediation, wastewater treatment, energy production, biofuels, bio-based plastics, and bio-pesticides.

The economics of the use of hemp products are a subject of ongoing debate, research and development, and trade analysis (Fike 2016). Although these available economic data are still limited, the hemp industry continues to evolve and invest (Source: BDS Analytics Newsletter 2019; https://bdsa.com/resources-summary/). Whether the hemp industry will grow depends on the political and economic framework in the European Union and other countries such as Canada and the U.S. The future development of hemp will also depend strongly on market demand for green products that are both beneficial to human health and have no impact on the environment.

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