Industrial Crops and Products 68 (2015) 32–41

Contents lists available at ScienceDirect

Industrial Crops and Products

journal homepage: www.elsevier.com/locate/indcrop

New developments in fiber hemp (*Cannabis sativa* L.) breeding

Elma M.J. Salentijn[a], Qingying Zhang[b], Stefano Amaducci[c], Ming Yang[b], Luisa M. Trindade[a,*]

[a] Wageningen UR Plant Breeding, Wageningen University and Research Centre, P.O. Box 386, 6700 AJ Wageningen, The Netherlands
[b] Industrial Crops Research Institute, Yunnan Academy of Agricultural Sciences, Kunming, PR China
[c] Istituto di Agronomia, Genetica e Coltivazioni erbacee, Facoltà di Scienze Agrarie, Alimentari e Ambientali, Università Cattolica del Sacro Cuore, Via Emilia Parmense, 84, 29122 Piacenza, Italy

ARTICLE INFO

Article history:
Received 22 April 2014
Received in revised form 24 July 2014
Accepted 8 August 2014
Available online 2 September 2014

Keywords:
Hemp
Fiber quality
Breeding
Genetics

ABSTRACT

Fiber hemp (*Cannabis sativa* L.) is a sustainable and high yielding industrial crop that can help to meet the high global demand for fibers. Hemp can be grown for fiber, seeds, and/or for dual purpose in a wide range of geographic zones and climates. Currently the main hemp producing regions in the world are China, Europe, and Canada. The number of new cultivars developed for each of these regions has gradually increased, with each region producing its own typical hemp cultivars for different purposes. In this article, the state of the art of fiber hemp breeding programs in Europe, China, and Canada are reviewed. The breeding strategies and tools used in the breeding of hemp cultivars are discussed. We also provide an overview of genetic diversity in hemp for different traits. In addition, the current knowledge of the main breeding goals for fiber hemp, which are an improvement of fiber quality and fiber yield, breeding for specific cannabinoid profiles, control of flowering behavior, male flowering control, and breeding of cultivars for specific environments are evaluated. Lastly, we discuss the inestimable value of next generation technologies to breed new hemp cultivars that are suitable for a biobased economy.

1. Introduction

Hemp (*Cannabis sativa* L, $2n = 20$) is one of the world's oldest cultivated annual crops (C3 annual), traditionally grown for its long and strong bast fibers and seeds. In most Western countries the cultivation of hemp vanished or was interrupted for decades as a result of competition with other feedstock's such as cotton and synthetic fibers, high labor costs, and the prohibition of cultivation due to the use of cannabis (*C. indica*) as a narcotic. Only in Eastern Europe, the former Soviet-Union and China has a substantial hemp industry survived (De Meijer, 1995). In the late 1970s and the early 1980s, the average hemp planting area once reached about 160,000 ha in China. After that, the cultivation area declined because of the above-mentioned reasons. The crop can be grown in a wide range of geographic zones of climate, and is well adapted to most regions of the world. China, Europe, and Canada are the three most important hemp planting regions in the world. According to FAOSTAT (excluding Canada), in 2011 hemp was cultivated globally on 61,318 ha, of which 11,400 ha in China, 14,344 ha in The European Union, and 15,720 ha in Canada (Source: Health Canada).

1.1. Products

Hemp is involved in a diverse range of products, and has integrated many agro-industrial fields such as agriculture, textile, bio composite, paper-making, automotive, construction, bio-fuel, functional food, oil, cosmetics, personal care, and pharmaceutical industry (Fig. 1). Traditionally, hemp bast fiber is used in textiles, paper pulp, and materials for building and insulation. Hemp hurds (also termed 'shives'), the woody and lignified core tissues of the stems, are used as horse-bedding, pulping, and concreting (Elfordy et al., 2008; Karus and Vogt, 2004). Besides the traditional uses, novel applications for fiber hemp (fibers/biomass) are being developed. The high cellulose content of hemp cell walls (Amaducci et al., 2000) together with the relatively high productivity make hemp biomass an interesting renewable feedstock for energy production (Hanegraaf et al., 1998; Prade et al., 2011, 2012a,b; Ragit et al., 2012), for the production of second generation bio-ethanol (Gonzalez-Garcia et al., 2012) and as a reinforcement in 'green composite' materials (Khalil et al., 2012; Shahzad, 2012) and concrete

* Corresponding author. Tel.: +31 317 482127.
E-mail address: luisa.trindade@wur.nl (L.M. Trindade).

http://dx.doi.org/10.1016/j.indcrop.2014.08.011
0926-6690/

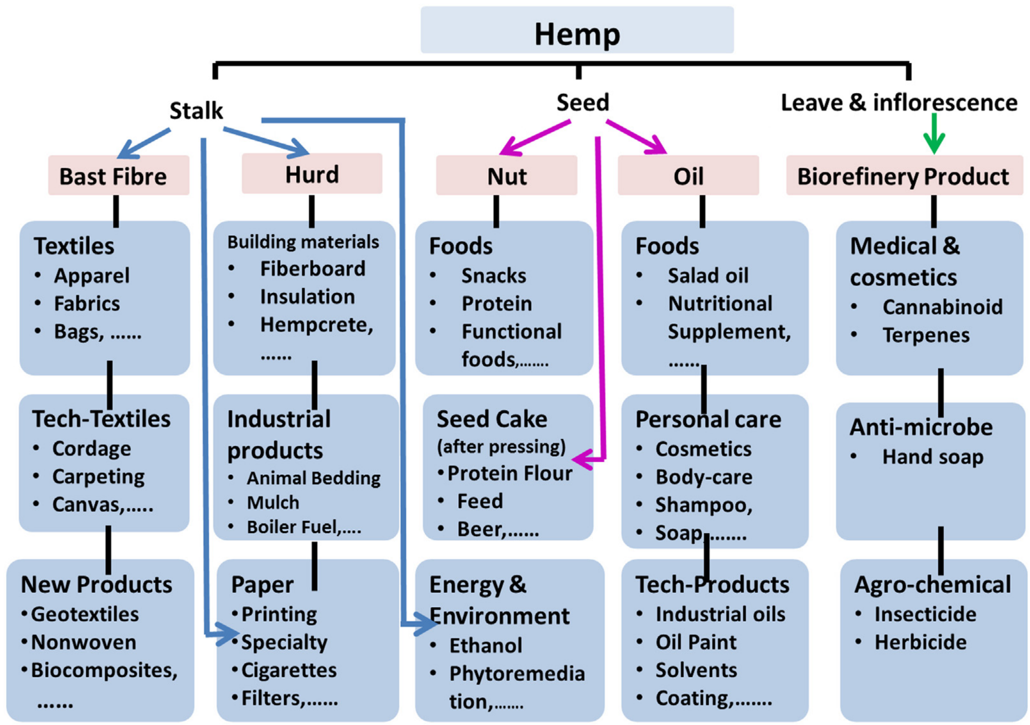

Fig. 1. Flowchart of multi-purpose hemp utilization.

(Elfordy et al., 2008). It is estimated that the global market for hemp consists of more than 25,000 products.

1.2. Yield

Hemp may potentially yield 25 t ha^{-1} above ground dry matter, 20 t ha^{-1} stem dry matter and 12 t ha^{-1} cellulose (Struik et al., 2000) but in many cases the yield varies. For instance, in Northern Italy total dry matter yield (cv. Futura 77) ranged from 18.7 to 8.3 t ha^{-1} over years and locations (Amaducci et al., 2000). In general cellulose yield is 7–10 t ha^{-1} (Zatta et al., 2012). The yield of the dry bast fiber varies from 1.2 to 3.0 t ha^{-1}, and seed yield from 0.7 to 1.8 t ha^{-1}. Industrial hemp production statistics for Canada indicate that average yield of seeds is about 0.78 t ha^{-1}, and an average 5.9 t ha^{-1} of straw, which can be transformed into about 1.45 t ha^{-1} of fiber (Johnson, 2013).

1.3. Hemp fiber

At present, hemp has been re-discovered as an interesting sustainable (Amaducci et al., 2000; Struik et al., 2000; Van der Werf and Turunen, 2008) high yielding industrial fiber crop (Van der Werf et al., 1996) that can help to meet the high global demand for fibers (Shui and Plastina, 2013). Hemp stems can be divided in a 'bark' or 'bast' section, corresponding to the tissue located in the outer part of the stem outside the vascular cambium, and the 'woody core' which is located inside the ring of vascular cambium and consists of lignin rich xylem tissue. The primary bast fibers (elementary fiber about 20 mm. to 50 mm. long) and secondary bast fibers (about 2 mm long) are derived from the vascular bundles in the bark of stems whereas the core fibers are located inside of the vascular cambium in the woody core (0.5–0.6 mm long) (De Meijer and Keizer, 1994; De Meijer, 1994; Mediavilla et al., 2001; Van der Werf et al., 1994). The primary bast fibers of hemp are made up of bundles of pericyclic elementary fibers that are characterized by thick and lignified cell walls. They are composed of cellulose (~55%), hemi-cellulose (~16%), pectin (~18%), and lignin (~4%) (Garcia-Jaldon et al., 1998).

Although hemp has the potential to produce fiber of excellent quality, the cultivars currently available deliver fiber of variable quality. A better understanding of the key factors determining fiber quality, and how these can be regulated, is of crucial importance for breeding fiber hemp. This article provides an overview of the state of the art with regard to hemp breeding and the possibilities of novel molecular breeding approaches to increase the value of industrial hemp.

2. Genetic variation in hemp

Hemp (*C. sativa* L.) can be classified according to different attributes including: (i) population type such as wild and naturalized populations, landraces, and cultivars; (ii) plant-use as fiber cultivars (for long fibers or for pulp), seed cultivars, drug strains, and ornamentals (De Meijer, 1995; De Meijer and Keizer, 1996); (iii) flowering time, which includes early ripening, intermediate-ripening, late-ripening cultivars; (iv) gender, whether they are dioecious or monoecious cultivars, and (v) geographic origin, e.g. North-type and South-type cultivars in China. Hemp is believed to have originated in Central Asia, and several advocate for two centers of diversity, Hindustani and European–Siberian (Zeven and Zhukovsky, 1975). There is still debate over the taxonomic organization of the genus *Cannabis*. Some authors have proposed a monotypic genus, *C. sativa*, while others state that two species can be distinguished, *C. sativa* and *C. indica*, and maybe even a third species *C. ruderalis*. On the basis of allozyme data for 157 accessions from diverse geographic origin, Hillig (2005) recognized three gene pools, *C. sativa*, *C. indica* and *C. ruderalis* and suggested a polytypic concept (=having several variant forms, especially subspecies or cultivars) of Cannabis, with seven putative taxa. The characteristics attributed to such subspecies have generally evolved as a result of geographical distribution or isolation. Russian botanists recognized four 'eco-geographical' groups