Chapter 1
Hemp Production

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Abstract This chapter reviews hemp production with emphasis on research challenges and opportunities. *Cannabis sativa* L. is an annual, cosmopolitan plant belonging to the genus *Cannabis.* Among a number of varieties, the economic significance have *Cannabis sativa* var. *sativa* and *Cannabis sativa* var. *indica*, commonly referred to as industrial cannabis/hemp and medical cannabis/medical marijuana, respectively. The in-between varieties are differentiated by around one hundred organic chemical compounds known as cannabinoids. The crucial distinction between industrial and medical cannabis is the content of the principal psychoactive cannabinoid – tetrahydrocannabinol (THC) in relation to non-psychoactive ingredient – cannabidiol (CBD).

Hemp is cultivated for biomass and fiber that constitute feedstock for industrial uses such as energy, construction and automotive markets and for hempseeds that are components of functional foods, animal feeds and medicinal products. The productivity of hemp is affected by both environmental and agronomic factors and their interaction. The hemp plants can act as retardants inhibiting weed growth, as natural insect repellents, and as a limiting factor of nematode growth in soil. The plants are capable of reducing greenhouse gas emissions by binding approximately 2.5 tons of CO_2 per ha and improving soil quality by phytoremediation of heavy metals. Under international and many national laws, industrial cultivation and provision is strictly regulated while medicinal plants are allowed only for medical and scientific purposes. For instance, according to Polish legislation on counteracting drug addiction all the hemp plantations can be established in delimited

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areas upon permission and when the content of psychoactive constituents does not exceed 0.2% on a dry matter basis while the other specific legislation is intended for particular nutritional uses and medical devices.

The future research on hemp production should be orientated towards breeding new varieties resistant to environmental stresses, optimization of agricultural treatments to improve effective uptake of nutrients, and modeling canopy structure in order to adapt the production to a changing environment.

Keywords Physiological parameters · Agrotechnical factors · Environmental impact

1.1 Introduction: Historical Background/Origin/Ancestry

Cannabis sativa L. (2n = 20) is a common plant that has been known since the dawn of humanity (Schultes 1970). This annual plant belongs to the botanical family *Cannabaceae,* and it is known under various names around the world: *konopie siewne* in Poland, *hemp* in English-speaking countries, *chanvre* in France, *konopi* in the Czech Republic, *konoplja* in Croatia, *hanf* in Germany, *kender* in Hungary, *cânepă* in Romania, *canapa* in Italy, *hennep* in the Netherlands, *maconha* in Portugal, *cannabis* in Spain, and *konopli* in Ukraine.

Paleobotanical and archaeological research indicates that cannabis has been known already in 6.000–8.000 BC, and its cultivation dates back to around 10.000–12. 000 BC. According to Li (1974), cannabis stems were used in the production of fibre and paper. Seeds with both psychoactive (*ma fen*) and non-psychoactive (*ma tze*) properties were grown in traditional Chinese medicine. Three geographic origins of cannabis have been postulated. The first independent trail begins in the Caucasus and the Altai Mountains in Central Asia (De Candolle 1884), from where cannabis spread east to China, south to India and west to Europe. The second trail leads from northern Afghanistan and the Hindu Kush mountains in Pakistan to India or China (Vavilov 1926). The third place of origin of *C. sativa* were the Himalayan foothills, the Hindu Kush mountains in South Asia (Sharma 1979) or India. These finding indicate that *C. sativa* originated in Asia, in particular in China and India where it was first cultivated by humans. Cannabis subsequently spread through the Middle East and Russia to reach Africa and Europe. The fact that the first paper mill in Europe was built by Muslims in 1150 provides evidence for the above. In the following 850 years, paper was manufactured mainly from hemp. In the sixteenth century, cannabis reached South America with Spanish explorers, and it was first introduced to Chile and Peru. The species then spread to North America, including Canada and the United States.

According to historical sources, hemp was classified by Linnaeus as *Cannabis sativa* L. in 1753. The second species, *Cannabis indica,* was identified by Lamarck in 1783, and the third species, *Cannabis ruderalis,* was classified by Janischevisky in 1924. Since then, the taxonomy of the species has been relatively well explored.

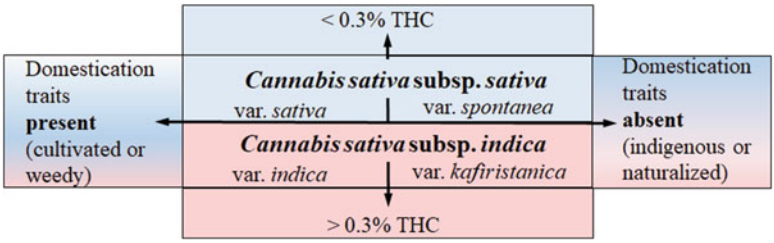

Fig. 1.1 Classification of *Cannabis sativa* according to Small and Cronquist (1976), authors' modification. THC – tetrahydrocannabinol. The two-step hierarchical approach: first step discriminates horizontally between subsp. *sativa* vs. subsp. *indica* on the basis of THC content under and over 0.3%, respectively*;* second step discriminates vertically between varieties with different THC content on the basis of the presence *vs.* the absence of domesticated traits, respectively

Small and Cronquist (1976) analyzed 2500 cannabis plants grown under standard conditions and found that the analyzed population belonged to the same species of *Cannabis sativa* L. regardless of the content of biologically active substances in non-intoxicant, semi-intoxicant and wild plants. The controversy surrounding the contemporary taxonomy and nomenclature of cannabis, including its scientific and vernacular names, has been discussed by McPartland and Guy (2017). This species has different subpopulations or botanical varieties, two of which have economic significance: *Cannabis sativa* subsp. (var.) *sativa* and *Cannabis sativa* subsp. (var.) *indica*. These varieties are commonly referred to as industrial hemp and medicinal hemp/medicinal marijuana, respectively (Small and Cronquist 1976; Hill 1983; Gigliano 2001). McPartland and Guy (2017) on the basis of Small's taxonomic concept (Small and Cronquist 1976) provide an indication on the cannabis classification system assuming two-step hierarchy approach (Fig. 1.1). The first step discriminates between two subspecies with 0.3% THC content in dried female flowering tops while the second step discriminates between varieties within subspecies *sativa* and *indica* on the basis of domestication phase. The authors pointed out that the content of THC and CBD can differentiate cannabis variety identities through three types of chemovars: Type I: THC > 0.3%, CBD < 0.5%; Type II: THC > 0.3%, CBD > 0.5%; or Type III: THC < 0.3%, CBD > 0.5%.

Genetic studies of *Cannabis sativa* germplasm based on Random Amplified Polymorphic DNA RAPD markers not only demonstrated the separation of Italian, Hungarian and Korean germplasm groups, but also revealed variability in a mixture of genotypes from different locations and within the analysed cultivars of Carmagnola and Fibranova (Faeti et al. 1996).

Botanical varieties of *Cannabis sativa* L. differ in chemical composition, plant habit, agronomic requirements and suitability for processing (Datwyler and Weiblen 2006). Industrial hemp is classified as an agricultural crop. Industrial cannabis is generally characterized by a low (below 1%) content of THCA and a CBD:THC ratio higher than 1. In turn, hemp used in the pharmaceutical industry is classified as a horticultural crop. Medicinal marijuana is characterized by a high content of THCA and a low content of cannabidiolic acid (CBDA). Regardless of the

cultivation system, cannabinoids undergo partial or complete decarboxylation from acidic to neutral form (e.g. THCA → THC, CBDA → CBD) during drying, storage and thermal processing (Żuk-Gołaszewska and Gołaszewski 2018).

Due to a large number of geographically and climatically diverse forms, different races (*proles* in Latin) of cannabis have been proposed in the classification of cultivated plants. Race or *proles* is not recognized as a taxonomic category, and this term denotes different categories of selected cultivars and cultivar groups (Fryxell 1976). Races (*proles*) are helpful in resolving problems relating to the classification and terminology of cultivated plants. These taxa are given Latin or botanical names. Hemp races differ in the length of the growing season, plant height and yield. Northern races have a growing period of 50–60 days with cumulative temperatures of 800–900 °C and a considerably high seed yield. Plant height ranges from 30 cm to 50 cm. In turn, southern races have a growing period of 140–160 days with cumulative temperatures of 3500–4000 °C. These plants have a height of up to 4 m, and they are characterized by a relatively low seed yield (Hoffman 1961). Transitional races represent intermediate characteristics between northern and southern forms.

1.1.1 Botanical Description

The morphology of *Cannabis sativa* plants is determined by sex (male and female, dioecious and monoecious) and growing conditions. Female plants, known as głowacze in Polish, develop more leaves than male plants (płaskonie in Polish). Cannabis plants have straight non-branching stems that are covered with short, curved and oval hairs. Stems have 7 to 10 internodes between the root crown and inflorescences, and the longest internodes are found in the central part of the stem. Stem length ranges from 30 cm to 400 cm. Palmate leaves have petioles and 3–11 leaflets with an opposite arrangement in the lower and central parts of the stem and an alternate arrangement at the level of inflorescences. Leaflets are lanceolate, regularly serrate and covered with glandular hairs. Female flowers are arranged in panicles at the top of the stem. Flowers are green, without a perianth, with one pistil and two stigmata per flower. Male flowers are small and arranged in loose panicles at the top of the stem. Hemp plants grown in Marian Lewicki's farm in Linowiec are presented in Photo 1.1. The farm's scientific consultant, Krystyna Żuk-Gołaszewska, assists the farm in selecting the optimal methods of cannabis cultivation and disseminates knowledge on the practical applications of this plant species.

Cannabis plants have a taproot and numerous side roots with a length of up to 2 m. The main portion of the root system is located at a depth of 20–50 cm. In a study by Amaducci et al. (2008a), root biomass ranged from 2.41 to 3.21 t ha^{-1} and varied across the experimental years. The ratio of above-ground to below-ground biomass was determined at 5.46. The roots of hemp plants grown in a field in north-eastern Poland are presented in Photo 1.2.

Photo 1.1 Hemp plants var. Białobrzeskie grown in Marian Lewicki's farm in Linowiec, Poland

Root systems are characterized by considerable plasticity, but root growth is conditioned by numerous environmental factors, including metal and water levels in soil (Fitter 1991; Elisa et al. 2007). Exposure to copper led to a significant decrease in total root length, mean root diameter, root surface area and root volume. Less branched root systems absorb nutrients less efficiently (Fitter 1991), which is why copper treatments reduced root absorbing surface.

1.1.2 Phenological Growth Stages

Every living organism is characterized by specific stages of growth and development. The growth stages of plants are described based on their unique agrophenophases as well as with the use of a decimal coding system developed by Zadoks et al. (1974). The first plants to have been described by the proposed decimal code were cereals of the class Monocotyledoneae. Many scientists relied on the Zadoks scale to develop codes for plant species of the class Dicotyledoneae, including *Cannabis sativa* L. (Mediavilla et al. 1998; Mishchenko et al. 2017). Cereal growth stages are described on the BBCH scale which is derived from the

Photo 1.2 Roots of *Cannabis sativa* L. (Marian Lewicki)

names of the originally participating stakeholders: Biologische Bundesantalt, Bundessortenamt and CHemische Industrie. The abbreviation is said to unofficially represent the four companies that initially financed the scale's development: Bayer, BASAF, Ciba-Geigy and Hoehst. The BBCH scale is a system for the uniform coding of the phenological stages of cultivated plants. This standardized scale for describing the growth stages of agricultural plants is applied in different scientific disciplines, including agronomy, physiology, pathology, plant breeding and meteorology, and it is also used by farmers. The BBCH scale also eliminates linguistic barriers which still exist in science.

Cannabis sativa L. is usually a dioecious (unisexual) species, where individual plants develop only male or only female reproductive organs (flowers). Hermaphrodites are sporadically encountered in successive generations. *Cannabis sativa* is characterized by distinctive stages of growth and development, and four principal stages representing the life cycle of this plant have been described by Mediavilla et al. (1998). In secondary growth stages, the second digit of the code denotes the plant's sex, whereas the third and fourth digits indicate the developmental stage (Table 1.1).

Germination and Emergence (Principal Stage Code 1) Various processes take place inside seeds during germination and lead to the activation of the embryo. Seeds imbibe water, and the radicle emerges from the seed coat. *C. sativa* is characterized by epigeal germination, where the hypocotyl emerges and the cotyledons unfold

Table 1.1 Principal and secondary growth stages of hemp (Mediavilla et al. 1998)

Code	Description
0	**Germination and emergence**
0000	Dry seed
0001	Radicle apparent
0002	Emergence of hypocotyl
0003	Cotyledons unfolded
1	**Vegetative stage**
1002	1st leaf pair
1004	2nd leaf pair
1006	3rd leaf pair
1008	4th leaf pair
1010	5th leaf pair
10xx	Until last leaf pair
2	**Flowering and seed formation**
2000	Change of phyllotaxis on the main stem
2001	Flower primordia
Dioecious plant – male	
2100	Flower formation
2101	Beginning of flowering
2102	Full flowering
2103	End of flowering
Dioecious plant – female	
2200	Flower formation
2201	Beginning of flowering
2202	Full flowering
2203	Beginning of seed maturity
2204	Seed maturity
2205	End of seed maturity
Monoecious plant	
2300	Female flower formation
2301	Beginning of female flowering
2302	Full flowering
2303	Male flower formation
2304	Male flowering
2305	Beginning of seed maturity
2306	Seed maturity
2307	End of seed maturity
3	**Senescence**
3001	Leaf desiccation
3002	Stem desiccation
3003	Stem decomposition

above the soil to form the first assimilative leaves. The cotyledons are large, sessile and smooth with nonserrate edges. The optimal temperature for germination is 24 °C (Elisa et al. 2007). The minimal temperature for germination is 0 °C (van der Werf et al. 1995a). Germination usually takes 3–7 days (Clarke 1977).

Vegetative Stage (Principal Stage Code 1) The vegetative stage occurs between emergence and generative development, and it is characterized by steam and leaf growth. In hemp plants, the stem is hollow and unbranched, and it is grooved or furrowed to varying degrees (Heslop-Harrison and Heslop-Harrison 1958). All leaves have a petiole. True leaves have a single narrowly elliptic blade with serrate margins (Stearn 1970). During the vegetative stage, the plant forms up to five true leaf pairs and short internodes. The first leaf pair consists of a single leaflet. Internodes grow during dynamic stem elongation (Bócsa and Karus 1998). The number of leaflets increases from the second leaf, and every leaf pair has an odd number of leaflets, usually three to eleven (the first leaf pair has three leaflets, the third leaf pair has five leaflets, etc.) (Clarke 1977). Seven to twelve leaf pairs develop during the vegetative stage, and the relevant code is 10xx for the nth leaf pair (xx = 2n). Fibre hemp plants generally have unbranched stems.

Flowering and Seed Formation (Principal Stage Code 2) In male and female plants, the first flower primordia are indistinguishable and difficult to identify. Male primordia can be identified by their curved shape and round, pointed flower buds with five radial segments. In turn, female primordia are identified based on an enlarged symmetrical tubular calyx (Clarke 1977).

At present, the generative phase of male, female and monoecious plants can be easily identified. Flower formation is characterized by the appearance of the first closed male flowers (code 2100) and the opening of the first staminate flowers (code 2101). Female inflorescences are leafy and compact. Individual female flowers are small, green and inconspicuous, and they are hidden inside the perigonal bract (Pate 1994).

In dioecious plants, male and female plants generally occur in roughly similar proportions (Hoffman 1961). The inflorescences of male plants are strongly branched, with few or no leaves. Female inflorescences are leafy, stocky and unbranched. Female plants live 3–5 weeks longer than male plants, until the seeds are ripe. Monoecious plants produce male and female flowers. The flowering stage refers to female flowers. Male flowers usually appear when female flowers bloom on the tips of female branches. Flowering is uneven. The male flowering stage is reached when around 50% of staminate flowers in one plant are open and pollen is released, and flowering ends when 90% of all flowers are open (Table 1.1). In this phase, stem elongation slows down, and the number of leaflets per leaf decreases (Heslop-Harrison and Heslop-Harrison 1958).

Cannabis plants are anemophilous. Mature pollen grains are released by thecae and reach the stigmata where the male gametophyte develops. Pollen grains germinate on stigmata and produce pollen tubes. Generative cells divide to form two male gametes (generative and vegetative), and sperm cells reach pollen tubes. Pollination takes place when pollen grains are transferred from the male anther of a flower to the

female stigma. The pollen tube penetrates the stigma and the pistil, and it enters the ovary and the ovule through the micropyle opening. The embryo sac is initially composed of a single cell containing eight haploid nuclei. Two polar nuclei are positioned in the centre of the embryo sac, and they fuse to form a diploid nucleus which is the secondary nucellus of the embryo sac. The secondary nucleus is diploid. The remaining six nuclei move to opposite poles of the embryo sac, and three nuclei are positioned at each pole. They are surrounded by cytoplasm to form three naked cells. One of the three cells on the side of the micropyle opening is an egg cell, and the remaining two cells are synergids. The three cells at the opposing pole are the antipodal cells. Pollination is followed by fertilization when the male gamete (sperm) fuses with the female gamete (egg cell). The pollen tube with two sperm cells penetrates the stigma and the pistil, and it enters the ovary and the ovule through the micropyle opening. Inside the ovule, sperm cells are released by the pollen tube and fertilization takes place. One of the sperm cells fuses with the egg to form a diploid zygote which further develops into an embryo. The second sperm cell fuses with the secondary diploid nucleus of the embryo sac to form a triploid cell (3n) that gives rise to triploid nutritive tissue – the endosperm. The ovule develops into a seed.

Senescence (Principal Stage Code 3) The seed maturation stage is defined for dioecious female plants (code 2306). The female flower has a small green organ, the bract, which completely encloses the ovary from which two stigmas protrude. This sheath is covered with slender hairs and stalked circular glands secreting resin containing cannabinoids (Stearn 1970). The seeds (achenes) turn hard, and seed shedding begins. Single seeds take 3–5 weeks to mature. Seed maturity is reached when 50% of the seeds are hard and have a characteristic shape and size. Cannabis seeds, referred to as achenes, are oval or ellipsoid in shape, somewhat flattened and grey-green in colour. The seed coat is shiny, and it takes on a matte appearance as the seed grows older. Cannabis seeds are 2–6 mm long, with a diameter of 2–4 mm and 1000 seed weight of 13–25 g. The germination capacity of cannabis seeds declines rapidly, which is why plants should be grown from the most recently harvested seeds (Heslop-Harrison and Heslop-Harrison 1958; Sacilik et al. 2003).

The phenological phases of *C. sativa* described by Mishchenko et al. (2017) are largely based on the decimal coding system developed by Zadoks et al. (1974). According to the authors, stage 4 does not occur in hemp plants (Table 1.2).

Table 1.2 Growth stages of *Cannabis sativa* L.

Code	Description
0002	Emergence of expected plants
2000	Flower induction of all plants
2102	Dioecious male flowering of all male plants
2202	Dioecious female flowering of all female plants
2302	Monoecious flowering of all monoecious plants
2204 or 2306	Seed maturity of female or monoecious plants

Mishchenko et al. (2017) relied on the research conducted by de Meijer et al. (1992) and de Meijer and Keizer (1994) to describe growth stages in 50% of the population in a given phenological phase. Code 2102 denotes dioecious male flowering in male plants, code 2202 represents dioecious female flowering in female plants, code 2302 indicates monoecious flowering in monoecious plants, and codes 2204 or 2306 denote seed maturity in female and monoecious plants. The proposed approach has useful implications for the cultivation of *C. sativa* plants.

The proposed code is a useful tool for identifying growth stages in hemp plants. Harvest date significantly influences the yield and quality of hemp plants used for various purposes. Plants grown for fibre should be harvested during male flowering (code 2012) or monoecious flowering (code 2302). In turn, plants cultivated for seeds should be harvested during seed maturity of female (code 2204) or monoecious plants (code 2306) (Bócsa and Karus 1998). In plants used in the production of essential oil, the recommended harvest date is 1–3 weeks before seed maturity (code 2203 and 2305) (Meier and Mediavilla 1998). However, regardless of the intended use (fibre, seeds), harvest should generally begin after seed formation (code 2204 or 2306) (Hennink 1997).

The decimal code supports the precise determination of phenological phases and facilitates cultivation. The described system promotes the application of fertilizers in the optimal growth stages (Mediavilla et al. 1998) and supports the identification of diseases that typically occur in a given stage (McPartland 1996). The decimal code is used in growth analyses, computer storage of data and statistical analyses. De Meijer et al. (1992) relied on the decimal code to determine phenological stages characterized by the highest cannabinoid content of inflorescences (code 2203 and 2305).

1.2 Seed Production

The seeds of *Cannabis sativa* have numerous applications, which creates new opportunities for cultivating this versatile crop. The area under cannabis continues to increase due to higher demand for cannabis seeds, preferably seeds from the last harvest.

1.2.1 Field Production Area and Certified Seeds

In 2017, the area under agricultural crops grown for seeds in Europe increased by 1.3% to 2,029,930 ha. France is Europe's largest producer of seeds (354,120 ha), including hemp seeds (www.escaa.org). In France, the area under hemp increased from 634.2 ha in 2010 to 1676.8 ha in 2017 (Table 1.3). The acreage of planted hemp was also high in Poland and Germany.

Table 1.3 Field area dedicated to the production of hemp seeds (ha) (www.escaa.org, accessed on 5 February 2019)

	Year								
Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
France	634.2	384.4	398.9	534.7	791.64	1094.9	1450.1	1676.8	1307.9
Germany	39.3	68.8	66.3	71.6	122.2	154.4	255.8	300.9	324.4
Hungary	101.5	8.8	54.6	28.3	35.5	87.5	93.5	111.2	36.2
Italy	8.71	10.58	16	22.5	36.4	8.13	138.4	157.1	195.5
Lithuania	nd	nd	nd	nd	55.5	139.5	332.4	174.2	129.8
Netherlands	1.0	nd	1.0	6.0	1.0	12	17	14	7
Poland	227.48	56.8	188.6	25.9	19.8	104.1	116.3	113.1	664
Romania	8.9	1.6	4.0	12.0	19.0	124.6	138.3	559.7	nd

nd no data

Table 1.4 Production of certified hemp seeds (t) (www.escaa.org, accessed on 5 February 2019)

	Year								
Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
France	668.8	479.5	500	481.3	821.5	1030.9	1131.8	1225.9	nd
Germany	33	70.4	72.2	50.5	109	250.8	193	295.5	nd
Hungary	8.1	9.4	8.1	15.2	12	11.2	16.0	18.0	nd
Italy	nd	1.7	1.3	5.4	3.6	10.5	34.0	0.0	nd
Poland	37	53	0.0	0.0	0.0	0.0	11.9	102.7	nd

nd no data

According to the Main Inspectorate of Plant Health and Seed Inspection (2019), Poland, the area under hemp crops cultivated for seeds was small and varied in 2010–2014. In the following 3 years (2015, 2016 and 2017), the area of seed plantations was similar, and it only marginally exceeded 100 ha. In 2018, field production increased sixfold to 664 ha. The above could be attributed to changes in legal regulations that facilitated the cultivation of hemp crops as well as increased supply of hemp seeds on the European market. In Poland, field area under hemp reached 6777.5 ha in 2017.

Certified hemp seeds are purchased mainly from France and Germany (Table 1.4), but in 2017, domestic production of certified seeds increased to 102.7 t. However, to the absence of local certified seeds, foreign varieties continue to be grown in Poland. An example can be HemPoland, a producer of hemp seed oil which relies on French varieties Futura and Felina. The company conducts research and shares its experience and knowledge with farmers and businesses. HemPoland also cooperates with international research institutions.

The European Industrial Hemp Association (EIHA) was founded in 2005, and it brings together 31 European countries that produce and process hemp seeds with various cannabinoid content. In 2011, the EIHA became a member of Technical

Committee 411 for Bio-Based Products of the European Committee for Standardization (CEN/TC 411). The EIHA is also a member of the ASTM D37 Committee on Cannabis, the Expert Group on Bio-Based Products of the European Commission, the Biomass Supply Thematic Working Group of the European Bioeconomy Panel, and the Sustainable Bioresources for a Growing Bioeconomy Strategic Working Group of the Standing Committee on Agricultural Research (SCAR) (www.eiha.org).

1.2.2 Varieties

The development of monoecious varieties of *C. sativa* has contributed to an increase in seed yield and improvements in biomass (fiber) quality. This is a considerable breeding achievement because the existing knowledge on inheritable agronomic traits in hemp is still limited. However, hemp varieties that adapt well to a broad range of agro-ecological conditions are still in short supply. At present, hemp breeding programs are initiated to pursue two major goals. The first is the industrial use of hemp, including hemp fiber which is qualitatively superior to woody core fiber for the production of paper pulp, and the production of oil from hemp seeds (Hennink 1994). Hemp biomass is also an excellent renewable source for energy generation. The second goal is the extraction of biologically active substances (cannabinoids) for medicinal use.

The majority of hemp varieties grown for industrial purposes are monoecious varieties, characterized by high yields, high processing suitability, early flowering and tolerance to a wide range of agro-economic conditions. The common catalogue of varieties of agricultural plant species has been published since 1975 in accordance with the provisions of Article 17 of Council Directive 2002/53/EC of 13 June 2002 on the common catalogue of varieties of agricultural plant species. The 37th complete edition of the catalogue, published in the Official Journal of the European Union 2019/C13/01, lists 68 varieties, including 8 Polish varieties. French, Dutch, Italian, Spanish, Hungarian varieties as well as conservation varieties from Latvia are also listed. The oldest Polish variety is Białobrzeskie, which was included in the catalogue in 1967, whereas varieties Glyana and Henola were registered in 2017 (Table 1.5).

1.3 Environmental Requirements

Cannabis sativa is very sensitive to environmental factors, including soil conditions, temperature and water availability. Malceva et al. (2011) and Stafecka et al. (2016) demonstrated that cannabis yields were more influenced by weather conditions during the growing season than by agronomic factors.

Table 1.5 Characteristics of selected varieties of *Cannabis sativa* L.

Białobrzeskie (Poland) – cultivated mainly for fiber. Plant height – 220 cm; straw yield – 14.9 t ha^{-1}; seed yield – 690 kg ha^{-1}; 1000-seed weight – 14.6 g; cellulose content – 48.2% NF DM; fat content of seeds – 34.8% DM; field certification – 116% (COBORU[a] 2017).
Glyana (Poland) – cultivated mainly for fiber. Straw yield – 12.6 t ha^{-1}; seed yield – 719 kg ha^{-1}; 1000-seed weight – 16 g; fat content of seeds – 33.8% DM; average fiber content of straw; relatively high content of long fiber; cellulose content of straw – 43% NF DM; content of Δ^9THC in the dry weight of panicles – 0.006%; satisfactory plant health (COBORU 2017).
Henola (Poland) – cultivated for seeds; seed yield – 1620 kg ha^{-1}; straw yield – 8.1 t ha^{-1}; 1000-seed weight – 15.9 g; fat content of seeds – 34.5% DM, trace amounts of Δ^9THC in the dry weight of panicles (0.01%); early to very early flowering and seed maturation; very short plants; resistant to lodging; satisfactory plant health (COBORU 2017).
Futura (France) – late maturity; inflorescence yield – 3.0 t ha^{-1}; stem yield at seed maturity – 8.34 t ha^{-1}; essential oil yield – 9 L ha^{-1} (Baldini et al. 2018).
Finola (Finland) – dioecious variety; short plants; resistant to lodging; branching absent or weak; photo-inhibition of inflorescence effectively prevents the production of mature seeds; fine fiber is more comparable to flax than hemp; low seed and biomass yield; growing season – 115–120 days (Callaway 2004a).

[a]COBORU = Research Center for Cultivar Testing

1.3.1 Soil

Cannabis thrives on fertile soils that are weeded and maintained in good condition. It can be farmed on both mineral and peat soils that are abundant in humic compounds and lime. Soils belonging to a very good and good wheat complex and a very good and good rye complex (according to the Polish soil quality classification system) are most suitable for cannabis cultivation. The highest yields are obtained on deep and porous soils with water table depth of more than 80 cm. The seed yield of cannabis cultivated on podzolic sandy loam ranged from 1050 to 2557 kg ha^{-1} seeds (Malceva et al. 2011). The most important factor is soil pH which should be close to neutral or slightly alkaline. In a study by Stafecka et al. (2016), hemp was grown on humic-podzolic gley soil with 6.5% organic matter content, pH 7.0, phosphorus (P_2O_5) content of 145 mg kg^{-1} soil, and potassium (K_2O) content of 118 mg kg^{-1} soil. García-Tejero et al. (2014) cultivated hemp on soil with the granulometric composition of clay loam containing 300 g kg^{-1} of sand, 310 g kg^{-1} of clay and 390 g kg^{-1} of silt. Effective depth was 2.5 m, organic matter content was below 15 g kg^{-1}, and water-holding capacity was 170 mm m^{-1}.

1.3.2 Temperature

Cannabis is a thermophilic crop. Total temperature during the growing season ranges from 800 to 3500 °C, depending on the region of cultivation (northern, southern and intermediate). In the temperate climate, total temperature ranges from 2000 to 3000 °C. The optimal temperature for photosynthesis is 25–30 °C, subject to

genotype (Chandra et al. 2011). Hemp seeds can germinate already at 0 °C, and emerged seedlings are resistant to temperatures as low as −8 °C to −10 °C (Bócsa and Karus 1998). In a study by Sarsenbaev et al. (2013), spring temperatures ranged from 3.3 °C in March to 12 °C in April. The average temperature in June was 23 °C, and maximum temperature reached 43–44 °C. In non-irrigated/irrigated plants exposed to high temperatures, seed yield was determined at 93.9/330.4 kg ha^{-1} (var. Fedora) and 22.6/324.7 (var. Felina).

1.3.3 Water

Water is one of the key determinants of crop viability, including in cannabis (Cosentino et al. 2013). Hemp is generally regarded as a resource-efficient crop. However, Tang et al. (2018) demonstrated that long-term stress increased leaf senescence, decreased LAI, but retained total canopy N content. Cannabis is a water-intensive crop, and daily water requirements are estimated at 22.7 l per plant. Field-grown marijuana requires nearly 430 million L km^2 of water. During the growing season (May–September), total precipitation approximated 700 mm, and daily evapotranspiration was determined at 6–7 mm in May–July and 4 mm in September (García-Tejero et al. 2014). Irrigation compensating for 80–100% of evapotranspiration loss had no significant influence on yields which were more dependent on genotype. Lisson and Mendham (1998) found that irrigation in the amount of 30 mm and 60 mm of water had a significant effect on fiber hemp yield. In turn, in the study Grabowska and Koziara (2001) the hemp plants need a total rainfall of 200–300 mm. Additionally, the due to the well-developed root system, the plant is tolerant to short periods of drought.

1.4 Agricultural Aspects

Agronomic factors, including preceding crop, tillage, nutrient availability, seeding and plant protection, and the key limiting factors to fiber and biomass yield and seed oil composition.

1.4.1 Farming System

Cannabis plants can be grown indoors with artificial light, in greenhouses with natural light, artificial light or both, as well as outdoors under exposure to natural light (van Butsic and Brenner 2016). *Cannabis sativa* is grown mainly in the field around the world. The selection of the optimal growing site is a very important consideration which influences the growth, development, yield and health of plants.

Protein crops, root crops and cereals fertilized with manure are the most suitable preceding crops for cannabis.

Cannabis should not be cultivated in long-term monoculture. A 4–5 year rotation is recommended (Kilanowski 1974). Cannabis plants leave the soil in good condition and free of weeds such as couch grass. Cannabis plants have a well-developed taproot which decomposes after harvest and is an excellent source of humic compounds for the cultivation of cereals and root crops. Gorchs et al. (2017) demonstrated that cannabis was a highly suitable preceding crop for wheat that contributed to the sustainability of cereal-based cropping systems under humid rainfed Mediterranean conditions.

Cannabis is usually farmed in conventional tillage systems. After the preceding crop is harvested, soil should be skimmed to a depth of 8–12 cm and harrowed to eliminate weeds. Mineral soils are ploughed to a depth of 20–30 m, and peat soils – to a depth of 30–35 cm (Campiglia et al. 2017). In fields where cannabis is grown after perennial plants (grass, red clover), disking is the first treatment to remove the sod. In conventional tillage systems, soil is dragged and harrowed in spring before seeding (Kilanowski 1974). Strip tillage also contributes to rapid and uniform seedling emergence, and it enables cannabis plants to effectively compete with weeds.

1.4.2 Fertilization

Nutrients influence the growth and development of plants and determine crop yields and yield quality (van der Werf et al. 1995b; Papastylianou et al. 2018). Cannabis plants have a particularly high demand for nitrogen in early stages of development and growth. In general, hemp has high nitrogen requirements (Coffman and Gentner 1975; Amaducci et al. 2002). In hemp cultivated for fiber, nitrogen fertilization at a rate of 240 kg ha^{-1} increased biomass yield, stem dry weight and inflorescence weight by 37.3%, 48.2% and 16%, respectively. In addition, plant height and inflorescence length increased from 1.66 to 1.76 m and from 66.2 to 82.9 cm, respectively (Papastylianou et al. 2018). To minimize nitrogen loss, nitrogen fertilizers should be applied in split doses during seedling emergence and upon the formation of the third leaf pair (Mediavilla et al. 1998). According to Stafecka et al. (2016), the nitrogen rate that optimizes seed yield ranges from 60 to 90 kg ha^{-1}. The seed yield of hemp var. Purini with 41.2% oil content was influenced by the rate of N fertilization and ranged from 0.83 to 2.39 t ha^{-1}. Nitrogen fertilization generally influences plant habit, leaf surface area and the dry matter yield of stems (Struik et al. 2000). Nitrogen also determines the THC content of cannabis leaves and their position on the plant (Coffman and Gentner 1975). In a study by Hemphill et al. (1980), the THC content of leaves decreased from the top to the bottom of the plant. Bócsa et al. (1997) demonstrated that high nitrogen levels promoted a greater reduction in the THC content of older than younger cannabis leaves.

Potassium and phosphorus are also essential for the growth and development of plants. Potassium plays a major role in the regulation of water transport in plants. Finnan and Burke (2013) demonstrated that hemp has lower potassium requirements than other agricultural plants and that the optimal potassium fertilization rate for soils with moderate to high levels of potassium is >70 mg/L. In treatments supplied with 60, 90, 120, and 150 kg K ha^{-1}, significant relationships were not observed between hemp yields, the potassium rate or soil potassium levels relative to control (0 kg K ha^{-1}). Around 70–75% of the absorbed potassium was concentrated in the stem. Varied doses of K were applied in other studies. For example, Iványi and Izsáki (1996) found that 234 kg K ha^{-1} of potassium was incorporated into plants. Iványi et al. (1997) demonstrated that potassium fertilizer applied at 249 kg K ha^{-1} during the growing season increased stem yields by around 1 t ha^{-1}. Similarly to nitrogen, phosphorus plays an important role in plant function. Phosphorus is a structural component of nucleic acids and lipids, and it participates in protein synthesis. The demand for phosphorus and potassium is particularly high during flowering.

1.4.3 Seeding

Plant propagation material should be obtained from certified sources where seeds are bred specifically to produce only female flowers. Male plants should be identified in the flowering stage and eliminated (Żuk-Gołaszewska and Gołaszewski 2018). The length of the growing season of cannabis cultivars differs across climate zones and is closely correlated with flowering and harvesting dates. Early-sown cannabis is characterized by prolonged vegetative development and relatively longer stems (Sengloung et al. 2009). In the Polish climate, the optimal period for sowing cannabis is late April to early May (Burczyk et al. 2009). Similar sowing dates were recommended by Papastylianou et al. (2018). Hemp seeds should be sown at a depth of 2–3 cm. Medicinal cannabis should have a bushy growth habit with a large number of side shoots, numerous leaves and inflorescences. A low seeding rate leading to relatively low plant density per m^2 promotes a bushy habit. A higher seeding rate produces taller plants with fewer and more evenly distributed side shoots. The optimal density is 20,000 plants per hectare, but in some production systems, it can be increased to 30,000 or even 40,000 plants per hectare to maximize the quality of raw materials for pharmaceutical processing (García-Tejero et al. 2014; Hall et al. 2014). Stem biomass decreases with an increase in plant density. The self-thinning effect of cultivation in rows with a width of 12.5, 25 and 50 cm was relatively small. Generally, row width did not affect stem yield or quality. However, in early-grown plants, stem yields tended to decrease with an increase in row width (van der Werf et al. 1995b). Stafecka et al. (2016) analyzed four seeding rates (50, 70, 90 and 110 kg ha^{-1}) and found that 50 kg ha^{-1} was the optimal seeding rate. In a study by Burczyk et al. (2009), the optimal seeding rate was 30 kg ha^{-1}. The highest biomass yield was 13.3 t ha^{-1}. In turn, in hemp grown for seeds or

panicles, the highest yields were obtained when hemp was sown at 10–20 kg ha^{-1} and harvested at full panicle maturity.

1.4.4 Weeds, Diseases and Pest Control

Successful cultivation of hemp is determined mainly by agronomic factors. Tillage is an important farming operation which reduces weed infestation and decreases the prevalence of diseases and pests. In the production of hemp, the optimal preceding crops are plants that effectively eliminate weeds. Hemp plantations are infested with weeds that are ubiquitous on agricultural land. The predominant weed species include *Chenopodium album* L., *Lamium amplexicaule* L., *Viola arvensis* Murr., *Phallopia convolvulus* L., *Stellaria media* Vill., *Thlaspi arvense* L., *Polygonum nodosum* Pers., *Galinsoga parviflora* Cav. and *Elymus repens* (L.) (Heller et al. 2007). Hemp plants that are adequately supplied with nutrients effectively compete with weeds. Hemp should be cultivated in wide rows to facilitate mechanical weeding before plants are sufficiently tall to suppress weeds (Grabowska 2005). Weed infestation is reduced in dense stands. According to Campiglia et al. (2017), weed infestation was affected by nitrogen rate and seeding rate. Weed biomass was determined at 73 g per m^2, and it was reduced by 31.5% in stands with a density of 120 hemp plants per m^2.

Plant diseases are caused mainly by fungi which thrive in environments characterized by high moisture levels, high temperature and lack of airflow. Crop yields are most severely compromised by the fungal species of *Botrytis cinerea* and *Sclerolinia sclerotiorum*, especially in wet years (van der Werf et al. 1995a). In hemp growing regions, diseases of hemp are rare. However, Agrios (1988) estimated that 11% of fiber crops are lost to diseases. The common diseases affecting cannabis plants are presented in Table 1.6.

Diseases can be controlled by keeping the field idle for 4–5 years, destroying post-harvest residues, implementing crop rotation schemes and introducing deep ploughing. Hemp plants are generally grown without herbicides, fungicides or insecticides (Struik et al. 2000; Jankauskiene and Gruzdeviene 2010). According to the guidelines of the Institute of Plant Protection (2019), the range of plant protection agents is limited, and preventive application of fungicides in early stages of development appears to be an effective method of disease control. The plants grown for medicinal purposes is protected with biological agents to guarantee the safety and high quality of raw material. Typical hemp pests include the hemp flea beetle (*Psylliodes attenuata*) and aphids (*Aphis fabae*). Bird predation can also compromise hemp seed yields (so called "seed disappearance" problem).

Hemp plants are environmentally-friendly crops that act as retardants suppressing weed growth. They also repel insects and pests, and inhibit the growth of nematodes in soil.

Table 1.6 Common diseases affecting cannabis plants

Gray mold – caused by *Botrytis cinerea*, thrives in temperate regions with high humidity and cool to moderate temperatures. Seedlings succumb to damping off. It arises as a gray-brown mat of mycelium which becomes covered by masses of conidia (fungal spores). Stems become chlorotic. Enzymes released by *B. cinerea* reduce stems to soft shredded cankers. Stems often snap at canker sites. Gray mold may encircle and girdle stems, wilting everything above the canker. Fiber varieties become more susceptible after canopy shadows (McPartland 1996).
Hemp canker – caused by *Sclerotinia sclerotiorum*. Symptoms begin as water soaked lesions on stems and branches of plants in the early maturity. The lesions collapse into cankers and become darkly discolored. Affected areas take on a shredded appearance, and the pith becomes filled with a white cottony mycelium. Plants remain in this condition or wilt and fall over. By September, large black sclerotia develop on the stem surface or within the pith of dead stalks. Crop losses can reach 40% (McPartland 1996).
Stem cankers – caused by *F. graminearum* and *F. avenaceum* in cooler climates, and by *F. sulphureum* and *F. sambucinum* in warmer climates (McPartland 1996).
Downy mildew – caused by two *Pseudoperonospora* species that affect fiber varieties
Root rot – caused by *Sclerotium rolfsii*, mostly in southern temperate zones and the tropics. The disease affects both fiber and drug varieties (Ferri 1961).
Premature wilt (charcoal rot) – caused by *Macrophomina phaseolina.* Infected plants prematurely wilt, turn yellow, brown, and die. The disease reduces yields (McPartland 1996).

1.5 Physiological Parameters

In crop production, the term "efficiency" is used synonymously with "performance", and it is defined in thermodynamic terms as the ratio of energy output (carbohydrates) to energy input (solar radiation) (Monteith 1977). The efficiency of plants is determined by agronomic (variety/cultivar, production system, plant protection agents, fertilization) and environmental factors, mainly temperature and water supply. In most agricultural crops, total dry matter yield is strongly correlated with the availability of solar energy. It was found that the photosynthetic efficiency of plants producing around 1.4 g of carbohydrates per 1 MJ of solar energy was 2.4% higher (Monteith 1977). The amount of light that is intercepted during the growing season and the efficiency with which captured light is utilized are important considerations. In general, plants intercept only around 40% of solar radiation, and they utilize 0.3% of that energy. The intercepted amount is determined by the growth stage and leaf area.

1.5.1 Photosynthesis

The photosynthetic process is a valuable physiological tool for evaluating plant responses to environmental stressors, and it facilitates the selection of plants for cultivation under varied environmental conditions (Żuk-Gołaszewska 2008; Chandra et al. 2015). Plant productivity is the rate at which dry matter (tissues, organs or the entire plant after dehydration) is produced and accumulated per unit of

time (day, growing season, year) as a result of carbon assimilation (photosynthesis) and dissimilation, namely mitochondrial (dark) respiration or photorespiration. This dynamic concept is expressed by the amount of dry matter produced by plants per unit of area per unit of time (g cm^{-2} h^{-1}) (Pessarakli 2014). In the light of the above definition of plant productivity, Nalborczyk (1996) demonstrated that under optimal conditions, crop yield is determined by the rate of photosynthesis minus the biomass loss resulting from respiration and the quantity of assimilates transferred from plant organs which had developed before the emergence of plant organs that constitute the agricultural yield. In Cannabis plants of two chemotypes (drug and fiber) exposed to UVB radiation (daily dose of 6.7 or 13.4 kJ m^{-1}), the rate of photosynthesis was determined at 25.2 (drug) and 24.2 (fiber) μmol CO_2 m^{-2} s^{-1}, whereas transpiration reached 3.29 and 3.38 mmol H_2O m^{-2} s^{-1}, respectively (Lydon et al. 1987). In a study by Bazzaz et al. (1975), the maximum net photosynthetic rate ranged from 7.89 to 9.72 μmol CO_2 m^{-2} s^{-1}. This parameter was influenced by geographic location and temperature. In Cannabis plants grown in Nepal and Illinois, the rate of photosynthesis increased with a rise in air temperature from 20 °C to 25 °C. In turn, the photosynthetic rate of Cannabis plants grown in Jamaica and Panama increased with a rise in temperature from 20 °C to 30 °C. In a study by Tang et al. (2017), the net photosynthetic rate increased with a rise in leaf nitrogen content up to 31.2 μmol CO_2 m^{-2} s^{-1} at 25 °C. The analyzed parameter increased with a rise in leaf temperature to 25–35 °C, and it decreased when leaf temperature exceeded 35 °C. In high 9-THC yielding varieties of *Cannabis sativa* L., the highest rate of photosynthesis was determined at 19.82 to 25.54 μmol CO_2 m^{-2} s^{-1} (Chandra et al. 2015).

1.5.2 Chlorophyll Content

Nitrogen fertilizer rates should be optimized based on an accurate assessment of plants' nutritional status. Chlorophyll levels during growth and development can be used to determine the nitrogen content of plants, and to predict yields (Żuk-Gołaszewska 2008; Grove and Navarro 2013, Zuk-Golaszewska et al. 2015). In a study by Malceva et al. (2011), *Cannabis sativa* leaves with higher nitrogen content tended to be more abundant in chlorophyll ($R^2 = 0.774$). Exposure to heavy metals decreased the chlorophyll content of leaves by 30% relative to control plants and led to visible leaf chlorosis (Linger et al. 2005). Zielonka et al. (2017) demonstrated that chlorophyll concentration was determined by the growth stage, variety and fertilization treatment. In cannabis var. Białobrzeskie, chlorophyll content was highest at approximately 40–45 SPAD units in early stages of growth in treatments fertilized with sewage sludge and phosphogypsum at 100 kg ha^{-1}. Greater variations in the chlorophyll content of *Cannabis sativa* leaves (38–47 SPAD) were observed at full maturity. In the last stage of plant development, the chlorophyll content of senescing leaves decreased to 11–35 SPAD.

1.5.3 Chlorophyll Fluorescence

Photosynthetic efficiency can also be evaluated by measuring chlorophyll fluorescence emissions. Chlorophyll fluorescence is a robust indicator of photosynthetic capacity and the vitality of the photosynthetic apparatus in plants growing both in nature and under controlled conditions. Measurements of chlorophyll fluorescence support rapid and sensitive analyses of plant responses to disruptions in photosynthesis caused by multiple stressors as well as evaluations of the effectiveness of repair mechanisms and plants' ability to maintain homeostasis under adverse environmental conditions. Stress factors such as cold, drought, herbicide damage, atmospheric pollution and nutrient deficiency decrease the photosynthetic rate, compromise plants' photosynthetic efficiency and increase chlorophyll fluorescence (Kalaji et al. 2017). A chlorophyll fluorescence analysis carried out by Malceva et al. (2011) demonstrated that high rates of nitrogen fertilizer (100 kg N ha^{-1}) stimulated the photosynthetic performance of hemp plants. In a study by Linger et al. (2005), the photosynthetic rate of *Cannabis sativa* plants exposed to different concentrations of cadmium in soil (17 mg kg^{-1} and 72 mg kg^{-1} soil) decreased in treatments with higher Cd content. Similar results were reported by He et al. (2008) in *Oryza sativa* L.

1.5.4 Growth Parameters

The relative growth rate of plants, expressed as the ratio of leaf area to whole plant dry mass, can be interpreted as: (1) an indicator for comparing growth between different species (varieties) under identical environmental conditions or within species (varieties) under different environmental conditions; and (2) as an indicator of dry matter accumulation in the plant, characterizing the size and structure of the plant and its assimilating organs (Pietkiewicz 1985). Canopy structure parameters include: leaf area, leaf growth curve, pathogen infestation, leaf area per unit ground surface area, foliage surface area of a canopy, leaf angle and the degree of canopy shadows. Plant growth analysis can be performed to evaluate the growth rate of plants as well as biomass production and distribution, which are determined by growing conditions and agronomic factors such as mineral fertilization, seeding rate, plant protection, light conditions, water stress, salinity stress and plant response to UVB radiation, expressed with multiple indicators (Żuk-Gołaszewska et al. 2003; Hyer and Gotem 2004). Well-known and reliable growth and structural parameters of plants and canopies are presented in Tables 1.7a and 1.7b.

The above indicators are used for plant growth modeling, including the distribution and translocation of dry matter in plants during ontogenesis. They may also serve as criteria for evaluating the morphological plasticity of biomass-related parameters, stress resistance and adaptability to adverse environmental conditions.

Table 1.7a Plant growth indicators

LAR (Leaf Area Ratio) – the total area of assimilating organs (usually leaves) of a plant A divided by the dry mass of the entire plant. It is equal to the product of: • SLA (Specific Leaf Area) – the ratio of leaf area A to leaf dry weight W_L • LWR (Leaf Weight Ratio) – the ratio of leaf dry weight W_L to whole plant dry weight W. In a study by Żuk-Gołaszewska et al. (2003), which investigated the effect of UVB radiation on agricultural crops, LAR values were determined by plant species rather than UVB radiation. An analysis of common weeds revealed that LAR ranged from 440 to 700 in *Avena fatua*, and from 460 to 580 in *Setaria viridis*, which points to higher or lower environmental adaptability.	$LAR = \frac{A}{W}$
ULR (Unit Leaf Rate) – the rate of photosynthesis per unit area of leaf, the rate of increase in net dry weight of the whole plant (difference between total dry weight production and loss) per unit leaf area over minimum of 24 h. Depending on the rate of photosynthesis, the same leaf area or weight can produce a different amount of biomass, which is related to daytime/nighttime. ULR is positively correlated with the rate of photosynthesis, and negatively correlated with respiration. During plant development, ULR decreases due to leaf senescence. ULR increases with an increase in N content, and it is correlated with the protein content of plants, including the enzyme Rubisco (ribulose-1,5-bisphosphate carboxylase) involved in the dark cycle reactions of photosynthesis. A decrease in soil N content is followed by a decrease in ULR within a few days. Average ULR value in C3 plants is 2–10 g DM per m^2 per day, and it is fivefold higher in C4 plants (Kopcewicz and Lewak 2005).	$ULR = \frac{1}{A} \cdot \frac{dW}{dt}$
RGR (Relative Growth Rate) – used to quantify an increase in whole plant mass over a given period of time. RGR is the only indicator that can also be applied to non-photosynthetic biomass, i.e. to determine the rates of breakdown and utilization of storage compounds during seed germination (Kopcewicz and Lewak 2005).	$RGR = \frac{1}{A} \cdot \frac{dW}{dt}$

1.6 Harvest, Drying and Storage

Hemp harvesting dates are determined mainly by the production profile and differ in plants that are grown for medicinal purposes (inflorescences), fiber (stems) and oil (seeds). Inflorescences are harvested from August to September (Grabowska 2005). Plants grown for medicinal purposes should be harvested manually, stems should be separated from inflorescences which should be dried at a temperature of 40 °C for 15 h to obtain high-quality material. Dried material for pharmaceutical processing should have a moisture content of approximately 8% and should be stored at a temperature of 18–20 °C. Inflorescences should be free of leaves (which are usually removed manually), they should be of high quality and should be certified as normalized medical cannabis. The plants for medicinal use are evaluated for moisture content, health, the presence of heavy metals, pesticide residues and cannabinoid levels (McPartland et al. 2000; Upton et al. 2013).

In conventional production systems, stems and seeds are harvested simultaneously with a combine harvested. After harvest, the remaining straw is baled. Harvest poses the greatest problem in seed production. When seeds mature, hemp stems are already lignified, and they become entwined around machine parts during

Table 1.7b Canopy indicators

LAI (Leaf Area Index) – leaf area of the entire canopy A_c per unit ground surface area P. LAI indicates how many times the leaf area contains the surface area occupied by canopy, and it is used to calculate seeding rate. Too high plant density (number of plants per unit area) decreases leaf area. In a study by Daughtry and Walthall (1998), the LAI of cannabis plants was 8. According to Tang (2018), the LAI of hemp plants is determined by N fertilization, and it reached 6.4 at N fertilizer rate of 120 kg ha^{-1}, and 2.3 in the unfertilized treatment. Additionally, long-term water stress enhanced leaf senescence and reduced LAI. Zielonka et al. (2017) reported that the maximal efficiency of the photosynthetic apparatus in *C. sativa,* expressed as LAI, was 3.4 m^{-2}. This physiological parameter was determined by growth stage, agronomic factors (fertilization) and breeding progress (varieties Białobrzeskie, Tygra, Beniko). A close correlation was also found between chlorophyll concentration and LAI (Haboudane et al. 2002). Differences in LAI result from leaf shape and angle, the rate of photosynthesis and the light requirements of plants. In most monocotyledonous plants (cereals, grasses), leaf inclination angle is acute, which facilitates light penetration through the canopy. In shadow-loving plants, LAI may range from 5–8 to even 10.	$LAI = \frac{A_c}{P}$
CGR (Crop Growth Rate) – is a measure of the increase in size, mass or number of crops over a period of time. It is the product of ULR and LAI. An increase in LAI can compensate for a decrease in ULR, thus maintaining CGR at a relatively stable level (Kopcewicz and Lewak 2005).	$CGR = ULR \cdot LAI$

harvest. As a result, harvesting equipment has to be frequently cleaned, and it is often damaged. For this reason, hemp plants grown for fiber should be harvested before seed maturation (Čeh 2018). Harvested hemp seeds should be dried at low temperature to a moisture content of around 9–10%. Fast drying at high temperatures can crack, burn seed and damage seeds, thus compromising their nutritional value and germination rate (Callaway 2004b).

1.7 Raw Material and Uses

Today, monoecious cannabis plants are more widely cultivated due to their higher processing suitability, i.e. higher fiber and seed yields, and medical use (Small and Marcus 2002; Amaducci et al. 2008b). Hemp fiber, located in stem tissues, is characterized by high strength and resistance to putrefactive changes. The length of hem fibers is determined by the technical length of stems (referred to as hemp straw), which is measured from the root crown to the mid-inflorescence. Heuser (1927), who investigated *C. sativa* grown in the temperate zone, found that the cross-sectional shape of fibers was grape-like and deeply wrinkled at the top, hexagonal in the middle and circular at the stem base. The stem is covered with epidermis. Collenchyma, support tissue, is located next to the epidermis (Herse 1979). The next layer is made up of primary and secondary fiber bundles. Highly valuable primary fibers are located in the middle and at the top of hemp stems. Useless

secondary fibers, found at the bottom of the stem, are left in the field after harvest. During plant growth and development, secondary fibers form mechanical tissue, which keeps the plant upright and contribute to its stiffness. Individual fibers are 10–25 mm long, forked, with bluntly pointed tips. In a study by Thomsen et al. (2005), hemp fibers contained 73–77% w/w cellulose, 7–9% w/w hemicellulose and 4–6% w/w lignin. Hemp shives contained 48% w/w cellulose, 21–25% w/w hemicellulose and 17–19% w/w lignin. The content of the above components varied across varieties – Felina contained least lignin whereas Futura and Fasamo contained least cellulose. The color of fibers was determined by pretreatment, and it was brighter after wet oxidation and hydrothermal treatment compared with steam explosion.

Hemp fiber constitutes valuable raw material for textile fibers, it has excellent moisture absorption and release properties, air permeability, warmth retention, cold and warm sense, high temperature resistance, insulation, anti-ultraviolet, anti-radiation qualities, anti-mildew and antibacterial properties, and sound-deadening properties. Hemp fiber has been widely used in many fields and products, such as clothing, sails, rope, paper and medical supplies (van der Werf and van Geel 1994; Zhang et al. 2016). Whole plant biomass (20–30 t ha^{-1}) is used in the power industry and sustainable housing. Hemp-lime composite known as hempcrete is newly-discovered construction material (Gołębiewski 2017) obtained by mixing hemp shiv, water, lime–based binder and/or sand in appropriate proportions. Hempcrete is characterized by high strength, therefore it can be used in sustainable architecture for building insulation, including filling walls with wooden or steel construction frames. Hemp composite material is non-flammable and has desirable acoustic properties (Bevan and Woolley 2008). Hempcrete production does not generate any waste, and the material is 100% recyclable. Other advantages of hempcrete include naturalness, environmental potential and a healthy indoor environment in buildings where hemp shiv was used as construction material. Hemp can also be a suitable crop for the bio-economy as it requires low inputs for producing high biomass yields.

Hemp seeds have a high content of fat (25–35%), protein (20–25%), phytic acid, choline, trigonelline, lecithin, chlorophyll, vitamins K and E, iron, calcium, zinc, phosphorus and magnesium (Deferne and Pate 1996; Główczewska-Siedlecka et al. 2016). They have medicinal properties and are used in dietary supplements and herbal preparations. Additionally, Ferenczy (1956) demonstrated the antibiotic properties of cannabis seeds, a factor that may aid its winter survival. Adherent resin on the seed surface, as well as a surrounding mulch of spent cannabis leaves, may serve in this regard.

Dried flower buds, leaf and flower extracts are used in the treatment of many diseases, in particular chronic pain. Medicinal cannabis is generally characterized by a high content of tetrahydrocannabinolic acid (THCA) and a low content of cannabidiolic acid (CBDA). The psychotropic threshold for cannabis plants is generally estimated at 1% THCA. Varieties of *C. sativa* L. have different predominant traits that make them suitable for pharmaceutical applications. They differ in chemical composition which is determined by the proportions of around

100 identified organic chemical compounds – cannabinoids, natural metabolites produced by cannabis plants.

Medical cannabis has analgesic properties, and it alleviates the suffering of patients who experience chronic pain (Murnion 2015). Aizpurua-Olaizola et al. (2016) identified at least 113 different cannabinoids isolated from cannabis plants. Psychoactive Δ9-trans-tetrahydrocannabinol (THC or Δ9-THC) and non-psychoactive cannabidiol (CBD) are the most known and most therapeutically valuable cannabinoids. Cannabinoid extracts with high levels of THC and low levels of CBD are most widely used for therapeutic purposes. Cannabis plants exert psychotropic effects when their THC content approximates 1% (Small and Marcus 2002). Small and Beckstead (1973) identified 3 chemical phenotypes (chemotypes) of cannabis: chemotype I – THC > 0.3% and CBD < 0.5%, chemotype II – predominance of CBD and various concentrations of THC, and chemotype III – marginal levels of THC.

1.8 Markets and Marketing

Due to their multiple uses, *C. sativa* plants play an important role in the economy. An increase in hemp production has been noted recently, mainly in Canada, the USA, China, Australia, and many other countries (www.faostat.fao.org). The number of cannabis farms increased by 58% and the total area under cannabis cultivation increased by 91% in 2012–2016. Hemp production increased by 40% on steep slopes, in the vicinity of public lands and in areas of high environmental sensitivity, including an 80–116% increase in cultivation sites near high-quality habitats for threatened and endangered salmonid species (Van Butsic et al. 2018). The food processing sector is making efforts to minimize the environmental impact of production, reduce the levels of toxic residues, use by-products more efficiently and manufacture high-quality products with desirable nutritional and organoleptic properties.

The market value of hemp-based products is difficult to estimate accurately because it is a nascent industry in terms of regulations, and cannabis plants have a variety of applications. Canada, the largest country in the world to legalize cannabis, has dramatically reshaped the cannabis investment landscape (www.bdsanalytics.com). The market of hemp-based products has been growing rapidly. According to forecasts, legal cannabis revenue is projected to reach $ 23.4 billion in the USA, $ 5.5 billion in Canada and $ 3.1 billion in the rest of the world by 2022 (Fig. 1.2) (Arcview Market Research and BDS Analytics 2018).

By 2022, the European market of CBD extracted from industrial hemp and medicinal cannabis will exceed $ 4.2 billion, whereas the segment of industrial hemp products will reach the value of $ 1.9 billion. *Cannabis sativa* is a niche crop, cultivated on more than 33,000 ha in the European Union (2016). France is the Europe's biggest producer of industrial hemp, and the world leader in hemp-seed production accounting for 59% of the global total (www.escaa.org). In Poland, according to the Statistical Yearbook of Agriculture (2017), crop production in the

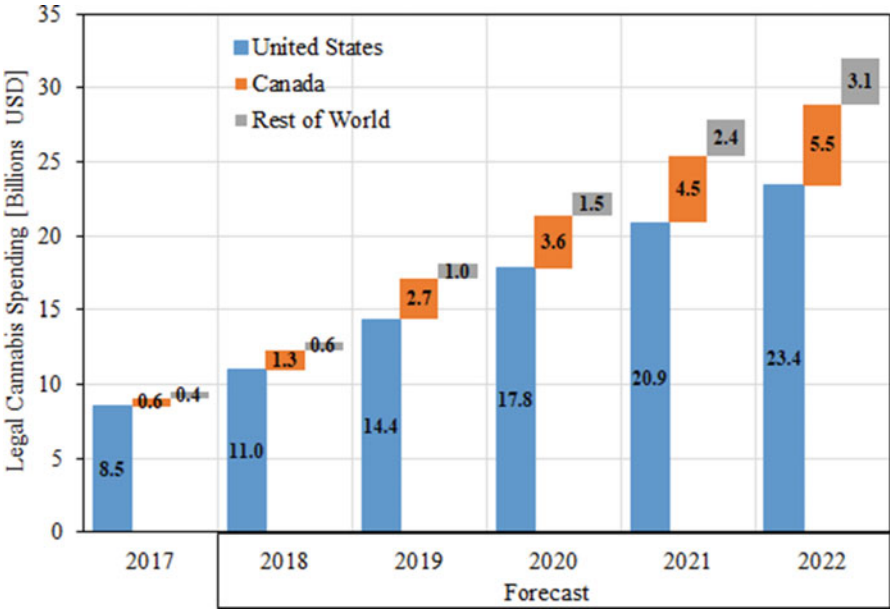

Fig. 1.2 Cannabis spending (Arcview Market Research and BDS Analytics 2018)

area of industrial plants including hemp is financed mostly under the EU Rural Development Program 2014–2020 where subsidies for cultivating fiber hemp reached 368,55 (PLN thous.) in 2016.

1.9 Environmental Performance and Impact

Hemp (*Cannabis sativa* L.) is a cosmopolitan species that is widely distributed around the world. Cannabis plants are eco-friendly crops that do not require extensive pesticide treatments, especially for weed suppression, and they can be cultivated in organic farming systems. Cannabis plants are tall and have a bushy growth habit, therefore they can protect other crops from wind in open spaces. *Cannabis sativa* is a good plant for soil phytoremediation (Linger et al. 2002). The species is capable of purifying soil and air, and it is resistant to environmental pollution. Therefore, cannabis farms can be established on fallow land and in areas degraded by industrial operations. Cannabis plants are characterized by high biomass yield and an extensive root system with numerous side roots. Although this trait is determined genetically, cannabis plants are highly adaptable and capable of absorbing and accumulating heavy metals in shoots and roots (Fitter 1991; Chiatante et al. 2005). Cannabis roots usually occupy the upper soil layer to a depth of 20 cm, but they can penetrate soil to a depth of up to 2 m (Zatta et al. 2012). These properties enhance the accumulation of Cu in cannabis roots and shoots (Angelova et al. 2004; Bona et al. 2007). A study of root morphology and protein expression revealed that *C. sativa* is tolerant to copper

(Elisa et al. 2007). In turn, heavy metals (Cd, Ni and Cr) were accumulated mainly in the roots and were partially translocated to aerial plant parts (Citterio et al. 2003). The cadmium content of cannabis shoots ranged from 14 to 66 μg g^{-1} (Linger et al. 2002). Under greenhouse conditions, Cd concentrations were highest in the roots where the maximum Cd content was determined at 830 mg (Cd) kg^{-1} (d.m.). Cadmium concentrations of up to 72 mg kg^{-1} (soil) had no negative effect on germination. At the end of the growing season, the average Cd content was determined at 42 mg (Cd) kg^{-1} (d.m.) in roots, 20 mg (Cd) kg^{-1} (d.m.) in stems, and 15 mg (Cd) kg^{-1} (d.m.) in leaves (Linger et al. 2005).

Recent years have witnessed a growing interest in the use of *Cannabis sativa* plants as a surrogate for chemical nematicides. In a cucumber farm severely affected by root-knot nematodes, the application of *C. sativa* leaves into the soil considerably reduced the nematode invasion (reduction in the number of galls, egg mass and nematode fecundity) relative to control. The incorporation of *C. sativa* into the soil as an effective organic nematicide against root-knot nematodes poses an alternative to traditional chemical treatments and minimizes environmental pollution (Kayani et al. 2012). Cannabis sativa has several advantages over conventional nematicides, including low cost, wide availability as well as environmental safety. Cannabis extracts significantly reduced the populations of phytopathogenic nematodes, bacteria, fungi, protozoans, insects, mites and weeds. Pure cannabinoids extracted from cannabis demonstrate similar properties (McPartland 1997).

In turn, hempseed oil showed absorbance in the UVC (100–290 nm) and UVB (290–320 nm) ranges and exhibited unique transmittance properties in the UVB and UVA (320–400 nm) spectrum. These findings indicate that hempseed oil has potential for use as a protectant against both UVA (source of oxidative stress in skin) and UVB radiation (Oomah et al. 2002). Hempseed oil containing CBD also exerts an indirect positive impact on the environment because cannabinol extracts have been shown to be helpful in smoking cessation. Hempseed oil contributes to an improvement in air quality by reducing the amount of tobacco smoke containing toxic tar compounds and heavy metals which are detrimental not only to human health, but also to the ecosystem.

Cannabis cultivation is eco-friendly and does not require plant protection agents. During growth and development, cannabis plants are capable of absorbing atmospheric carbon dioxide which is responsible for the greenhouse effect. Crops that absorb carbon dioxide, including cannabis, contribute to a reduction in greenhouse gas levels. A cannabis plantation with an area of 1 hectare is capable of absorbing 2.5 tons of atmospheric CO_2. Cannabis plants are also an abundant source of biomass for the generation of renewable energy, and the energy efficiency of cannabis can exceed that of wood and coal. This alternative source of energy minimizes tree felling and, consequently, prevents ecosystem degradation.

The area under cannabis has increased dynamically due to the numerous potential uses of the p, in particular in medicine. In the United States, the number of cannabis farms increased by 58%, the production of cannabis plants increased by 183%, and the area under cannabis increased by 91% between 2012 and 2016. An increase in the number of sites where cannabis is grown (80%) as well as their size (56% per site) has also contributed to the observed expansion. Cannabis production soared in

areas of high environmental sensitivity, and a 80%–116% increase in cannabis cultivation was reported in the proximity of high-quality habitats for threatened and endangered salmonid fish species (van Butsic et al. 2018). However, intensive production and transportation of cannabis is also energy intensive, and it has contributed to air pollution through higher emissions of carbon dioxide, nitrous oxides and airborne fungal spores (Mills 2012). Intensive cannabis cultivation, in particular in small farms, also exerts a negative impact on the local landscape.

The environmental impact of production is an important consideration. The life cycle assessment is a new approach to analyzing the environmental impact of a process or a product. In food production, this technique is used to analyze the authenticity of food products, their place of provenance, safety and nutritional value as well as environmental impacts of production and distribution systems; LCA contributes to improving environmental and economic efficiency in the food supply chain, taking into the account the effects exerted by raw material, production, distribution, packaging, sale and consumption. The method can also be applied to hemp plants which produce significant quantities of useful straw co-products that could act as temporary CO_2 storage (O'Mahony 2011). The LCA carried out by Casas et al. (2005) included the absorption of CO_2 during the growth of hemp plants, which conventionally is excluded from LCAs of biodiesels under the assumption that CO_2 absorption will be balanced out by the corresponding CO_2 emission during fuel combustion.

1.10 Legal Regulations

The production and processing of cannabis is governed by strict laws in many countries. In Poland, a state license is required to establish a cannabis plantation in a delimited area. Only certified or elite seeds can be sown, and growers can supply cannabis only to legitimate contractors who are registered by the voivodeship marshal. Cannabis production is regulated by the provisions of the Act of 5 July 2005 on counteracting drug addiction. In the above act, hemp is defined as fibrous-class *Cannabis sativa* L. plants where the total content of Δ-9-THC, Δ-9-tetrahydrocannabinolic acid and Δ-9-THC-2-carboxylic acid in flower buds and fruit buds containing resin does not exceed 0.20% on a dry matter basis.

Cannabis cultivation is also regulated by the Act of 7 July 2017 amending the provisions of the Act on counteracting drug addiction and the Act on the reimbursement of medicines, foodstuffs intended for particular nutritional uses and medical devices. Pursuant to Article 1 of the Act of 7 July 2017, the provisions of Article 33 the Act of 29 July 2005 on counteracting drug addiction (Journal of Laws, 2017, item 783) have been amended by inserting Articles 33a–33d: "Article 33a: 1. Cannabis plants other than fiber hemp, pharmaceutical extracts and tinctures, extracts from cannabis plants other than fiber hemp as well as cannabis resin other than fiber hemp resin, as stipulated in Annex 1 to the Act, may constitute pharmaceutical raw materials, as stipulated in Article 2, point 40 of the Pharmaceutical Law of 6 September 2001, for the production of prescription drugs, as stipulated in Article

3, section 4, point 1 of the Pharmaceutical Law of 6 September 2001, that may be placed on the market under a license granted by the President of the Office for the Registration of Medicinal Products, Medical Devices and Biocidal Products, hereinafter referred to as the President of the Office. 2. The license stipulated in section 1 hereinabove can be issued or denied, the data and documents which constitute a basis for granting the license can be modified, the term of the license can be prolonged and shortened, and the license can be revoked by a decision of the President of the Office. 3. The license stipulated in section 1 hereinabove shall be issued for a period of 5 years. Article 33b. 1. The application for: 1) granting the license stipulated in Article 33a, section 1 hereinabove, 2) modifying the data that constitute the basis for granting the license, 3) modifying the validity of the license shall be submitted by the responsible entity, as defined by Article 2, point 24 of the Pharmaceutical Law of 6 September 2001, to the President of the Office. 2. The provisions of Article 10, Article 18, Article 23, section 1, Article 29, section 1, Article 30, section 1, Article 31, section 1 and Article 33, section 1 of the Pharmaceutical Law of 2001, and the provisions of Article 36 of the Pharmaceutical Law of 6 September 2001 applicable to the licensing requirements stipulated in Article 20 of the said law shall apply to the application and the license stipulated in section 1 hereinabove. 3. The provisions of chapters 3 and 5 of the Pharmaceutical Law of 6 September 2001 shall apply to the pharmaceutical raw materials stipulated in section 1 hereinabove. 4. Prescription drugs stipulated in Article 33a, section 1 hereinabove shall be classified into schedules, as indicated by Article 23a, section 1, point 4 of the Pharmaceutical Law of 6 September 2001. Prescription drugs indicated in Article 33a, section 1 hereinabove shall not be prescribed by veterinary physicians. Article 33c. 1. The application for the license stipulated in Article 33a, section 1 shall indicate: 1) the name of the pharmaceutical raw material and the active ingredient; 2) packaging size (Journal of Laws, item 1458); 3) the name and permanent address of the responsible entity, as defined by the Pharmaceutical Law of 6 September 2001, submitting the application as well as the data pertaining to the manufacturer or manufacturers if the pharmaceutical raw material is not manufactured by the responsible entity; 4) list of documents attached to the application. 2. A copy of the license stipulated in Article 38, section 1 of the Pharmaceutical Law of 6 September 2001 shall be attached to the application indicated in section 1 hereinabove. 3. The specimen application and the detailed scope of the data and documents that constitute the basis for licensing pharmaceutical raw products for the production of prescription drugs containing cannabis plants other than fiber hemp, pharmaceutical extracts and tinctures, extracts from cannabis plants other than fiber hemp as well as cannabis resin other than fiber hemp resin, as stipulated in Annex 1 to the Act, shall be defined by a regulation of the minister competent for public health, taking into consideration special requirements regarding the proper administration of the drug, the patient's safety and the protection of public health. Article 33d. 1. The production of an active ingredient for the manufacture of pharmaceutical raw materials consisting of cannabis plants other than fiber hemp, pharmaceutical extracts and tinctures, extracts from cannabis plants other than fiber

hemp as well as cannabis resin other than fiber hemp resin, as stipulated in Annex 1 to the Act, shall involve the comminution of dried plant parts, physicochemical processes that lead to the production of the above substances, including extraction, and packing into bulk packaging, and it shall conform to the Good Manufacturing Practice for active pharmaceutical ingredients. 2. The provisions of chapter 3a of the Pharmaceutical Law of 6 September 2001 shall apply to the operations stipulated in section 1 hereinabove. 3. The production of pharmaceutical raw materials stipulated in section 1 hereinafter shall involve repackaging of the active ingredient from bulk packaging into primary and secondary packaging that will be distributed to pharmacies, and it shall conform to the Good Manufacturing Practice for active pharmaceutical ingredients. 4. The provisions of chapter 3 of the Pharmaceutical Law of 6 September 2001 shall apply to the operations stipulated in section 3 hereinabove." Article 2. The provisions of Article 6 of the Act of 12 May 2011 on the reimbursement of medicines, foodstuffs intended for particular nutritional uses and medical devices (Journal of Laws, 2016, items 1536 and 1579; Journal of Laws, 2017, item 1200) are hereby amended by inserting section 5a after section 5: "5a. The provisions of section 5 shall not apply to prescription drugs manufactured from pharmaceutical raw materials that have been licensed pursuant to the provisions of Article 33a, section 1 of the Act of 29 July 2005 on counteracting drug addiction (Journal of Laws, 2017, items 783 and 1458)". Article 3. This Act shall come into force 3 months after notification.

In the Netherlands, medicinal cannabis is available on prescription in pharmacies. Research and production of medicinal cannabis are monopolized by Bedrocan International under government supervision (Law on opium 2003). In turn, Canada is a pioneer in medicinal cannabis legislation. The Medical Cannabis Access Program came into force in 1999. Personal cultivation and commercial production of cannabis for medicinal purposes were legalized in 2016. In Canada, licensed producers who hold a valid permit may import cannabis and its derivatives for commercial use.

The next example describes the production and use of *Cannabis sativa* in Colombia. In Colombia, medicinal cannabis had been legally available on prescription already since 1986, but Law 1787/2016, Decree 613/2017 and Resolutions 577, 578 and 579/2017 created a legal framework for the production and sale of cannabis for medicinal purposes. Four types of licenses for the legal production of marijuana can be obtained from the government: 1. License for the manufacture of cannabis derivatives, 2. License for the cultivation of non-psychoactive cannabis, 3. License for the cultivation of psychoactive cannabis, and 4. License for the use of cannabis seeds. These licenses have different modalities, and they can be obtained for research, national use or export. Colombian law sets an example for the legalization of cannabis in Latin American countries such as Ecuador, Peru and Mexico. The newly adopted legal framework will place Colombia at the forefront of cannabis production and research, and it will boost revenues from the export of cannabis derivatives (cannabis flowers may not be exported) (information obtained privately).

1.11 Challenges

Hemp is the crop of the future because it has numerous industrial applications – it can be used as fiber, building material, composite material in the automotive industry, a source of oil and essential oils, animal feed and litter, briquettes and fuel. The medicinal and therapeutic use of cannabis poses a challenge. The yield and pharmaceutical quality of cannabis plants are determined mainly by plant variety and agricultural treatments, in particular sowing date, fertilization, seeding rate and watering. Cannabinoids, including tetrahydrocannabinol (THC), identified in cannabis exert analgestic effects, stimulate appetite and protect neurons. Cannabidiol (CBD) alleviates some symptoms of depression and mood-related disorders, and may help combat alcohol addiction.

Cannabis sativa is an eco-friendly plant species that requires few crop protection chemicals, suppresses weeds and inhibits the growth of selected pests such as the large white and the Colorado potato beetle because limonene and pinene – compounds responsible for its aroma – are potent insect repellents.

There is a need for standards and regulations on the cultivation and medicinal use of cannabis across the EU member states and in the world in order to breed varieties with desirable qualitative parameters and offer alternative treatment options.

Besides, industrial hemp is a promising energy crop that can be converted to bioethanol and biogas, and used as biomass for combustion. In open spaces, hemp plants perform esthetic functions and add diversity to monotonous landscapes.

It appears that future research into hemp cultivation should focus on:

- breeding new varieties that would convert solar energy into biomass more effectively, use water more efficiently, and be more resistant to multiple environmental stressors,
- optimization of agricultural treatments, including their effects on canopy structure, in view of more effective use of substrates (light, solar energy, carbon dioxide and water) to increase photosynthetic productivity and yields,
- modeling canopy structure in different varieties in view of crop yield forecasting and management under changing environmental conditions due to global warming, soil contamination, etc.

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