herba polonica
International journal edited by the Institute of Natural Fibres and Medicinal Plants
Vol. 65 No. 2 2019

Received: 2019-05-06
Accepted: 2019-06-20
Available online: 2019-06-30

DOI: 10.2478/hepo-2019-0012

REVIEW PAPER

Contribution of Polish agrotechnical studies on *Cannabis sativa* L. to the global industrial hemp cultivation and processing economy

JOANNA PONIATOWSKA[1], KAROLINA WIELGUS[2]*, MILENA SZALATA[2], MARLENA SZALATA[3], MARCIN OŻAROWSKI[2], KATARZYNA PANASIEWICZ[1]

[1] Department of Agronomy
University of Life Sciences
Dojazd 11
60-632 Poznań, Poland

[2] Department of Biotechnology
Institute of Natural Fibres and Medicinal Plants
Wojska Polskiego 71b
60-630 Poznań, Poland

[3] Department of Biochemistry and Biotechnology
University of Life Sciences
Dojazd 11
60-632 Poznań, Poland

*corresponding author: e-mail: karolina.wielgus@iwnirz.pl

Summary

Industrial hemp (*Cannabis sativa* L.) attracts increasing interest of growers, in relation to both industrial and medical purposes. Construction is the most promising area of the economy for hemp, and specifically, the fast-growing production of insulation and bio-composite materials.

The most significant factors affecting the final yield of hemp seeds and biomass include: climatic factors, i.e. influence of weather conditions that determines the content of cannabinoids in plants; genetic predisposition of the variety used as well as agrotechnical factors. The article provides information on the botanical characteristics of fiber hemp, hemp cultivation area, Polish monoecious varieties of industrial hemp, hemp's agricultural requirements, including: the demand for macroelements (nitrogen, phosphorus, potassium, calcium); choice of soil, pioneer crop, and field preparation; sowing timing and density; harvest time; water conditions; heat and light requirements for hemp. The review article is focused mainly on the results of studies carried out at the Institute of Natural Fibres and Medicinal Plants, data of the Agency for Restructuring and Modernization of Agriculture (ARiMR), Research Centre for Cultivar Testing (COBORU), European Industrial Hemp Association (EIHA), published in 2008 - 2018.

Key words: ***Cannabis sativa L., hemp, agrotechnical studies***

Słowa kluczowe: ***Cannabis sativa L., konopie, badania agrotechniczne***

INTRODUCTION

Industrial hemp (*Cannabis sativa* L.) has been known to humans for thousands of years [1–3]. The species originated in Asia [2, 4]. Hemp adapts to variable environmental conditions, and a number of literature sources indicate that its spread has always been correlated with sea and trade routes, mainly due to the large variety of its uses [5, 6].

In the 1930s, hemp was used in industry on a massive scale. Currently, after nearly 90 years, it attracts increasing interest of growers once again, related both to industrial and medical purposes. Record area of hemp plantations in Europe in 2016 amounted to 33,000 ha [7], while in Poland, the largest area was noted in 2017: 7,000 ha (data of Institute of Natural Fibres and Medicinal Plants, INF&MP).

Owing to its high content of phytocannabinoids, hemp has a high potential for pharmaceutical use, as a raw material for drug production. The negative perception of hemp and restrictions on its cultivation found globally are associated with the content of psychoactive phytocannabinoids, most notably Δ^9-tetrahydrocannabinol (Δ^9-THC) [8-10]. However, hemp is also a source of phytocannabinoids with antipsychotic, analgesic, anti-inflammatory, and anxiolytic properties, especially cannabidiol (CBD) [11-13]. Moreover, hemp seeds are an important source of polyunsaturated fatty acids (PUFA), amino acids, and vitamins [9, 14], and may improve metabolism and provide multiple other health benefits with regular consumption.

Hemp has a great industrial potential and has been used in numerous branches of industry, though, its dominant uses evolved over the years. Before finding cotton, hemp had been widely used in the textile industry [15]. Later, interest shifted towards the pulp and paper industry [7]. Currently, construction is the most promising area in the economy of hemp, especially the fast-growing production of insulation and bio-composite materials [16, 17]. The accelerating development of technology also brought on other interesting ideas, including the use of hemp in innovative applications in the automotive industry [18] and in medical implant manufacturing [19].

From the biological perspective, development is considered mainly associated with increasing plant productivity. Hence the need for selection of appropriate varieties and optimization of major agrotechnical factors, including sowing density and nitrogen fertilization level. Many authors now agree that the most significant factors affecting the final yield of hemp seeds and biomass include: sowing density [20-21], nitrogen fertilization level [22-23], and time of harvest [24-25]. Weather conditions and the genetic predispositions of the specific variety are also significant [26].

BOTANICAL CHARACTERISTICS OF INDUSTRIAL HEMP

In accordance with its botanical classification, hemp is an annual, wind-pollinated, monoecious or dioecious herbaceous plant in the family *Cannabaceae*, genus *Cannabis* [1, 3, 25, 27]. According to authors, the genus *Cannabis* is currently considered monotypic, including only the species *Cannabis sativa* L. The species comprises industrial hemp (*Cannabis sativa* L. var. *sativa*), primarily cultivated for fiber and oil, and drug-type hemp, or simply cannabis, (*Cannabis sativa* L. var. *indica*), cultivated for processing into marijuana or hashish. Hemp is considered very adaptable to diverse weather and soil conditions during vegetation, and therefore, multiple types and varieties have been described, with considerable biological and morphological differences and a number of uses. In literature, several basic classifications of hemp are listed. One is based on the plants' origin, biological characteristics, and biometric parameters. As reported by Cierpucha [20] and Zadrożniak *et al.* [25], this classification includes northern hemp – a dwarf variety with a short vegetation period of 60–75 days, and southern hemp – tall-growing with a vegetation period of 140–160 days. However, at our latitudes, the intermediate type is the most common.

Authors agree that all Polish hemp varieties represent the intermediate type: they have a vegetation period of 120–140 days, and grow from 150 cm up to 4 m tall (the latter in favorable weather conditions). According to Grabowska [28] and Burczyk [29], depending on the cultivation purpose, seed yield may range between 0.3 and 1.0 $t \cdot ha^{-1}$, straw yield – between 10 and 18 $t \cdot ha^{-1}$, and fiber yield – between 2.5 and 4.0 $t \cdot ha^{-1}$.

Another classification of *C. sativa* L. is based on Δ^9-THC (Δ^9-tetrahydrocannabinol) content, and comprises industrial hemp, containing less than 0.2% of the hallucinogenic Δ^9-THC, and drug-type hemp, which has psychoactive properties due to its Δ^9-THC content exceeding 0.2% [1, 25]. According to Grabowska *et al.* [28], the first hemp varieties cultivated in Poland were of the dioecious Central-European type, though the authors pointed out that this characteristic had a number of undesirable consequences, both in terms of harvest and processing. To eliminate these difficulties, monoecious hemp was bred, ensuring simultaneous maturation, uniform raw material, and a higher seed yield. Hemp is sexually dimorphic, and the male (staminate) and female (pistillate) plants are subject to distinctive developmental processes, both in terms of phenotype and individual development [26, 27]. As reported by Zadrożniak *et al.* [25], male plants complete vegetation approx. 4 weeks sooner than female plants.

First Polish experiments with cultivation of monoecious hemp began in 1956, and resulted with the registration of the first Polish monoecious hemp variety, Białobrzeskie, in 1968 [28]. Faux [30] reported that monoecy may differ in nature based on the proportion of male and female flowers, while Brook *et al.* [31] stated that on the basis of male and female flower distribution, monoecious plants may be classified into one of five types. Type one is defined by a marked majority of male flowers (80–90%). Type two is defined by a somewhat smaller, 60–80% share of male flowers and a 20–40% share of female flowers. Type three is the most significant, with "perfectly monoecious" plants having nearly equal shares of male (40–60%) and female (40–60%) flowers. Type four is defined by a lower share of male flowers (10–40%) and a larger share of female flowers (60–90%), while type five is defined by a marked majority of female flowers, exceeding 90%.

Currently, breeding work carried out by INF&MP is based on the seed reserve and individual selection methods [28]. Mandolino *et al.* [32] reported that the main difficulty in monoecious hemp cultivation is trait segregation and regression to the natural dioecious form. Except traditional cultivation, biotechnological methods for *in vitro* culture also exist [28]. Authors pointed out that treating male flowers with 2-chloroethylphosphonic acid (ethrel) in a monoecious hemp culture accelerates the achievement of monoecy, as the acid significantly reduces the share of male in favor of female flowers. Wielgus *et al.* [33] added that another purpose of transgenic hemp culture may concern the ability to modify selected use characteristics, such as resistance to pests and diseases; increased fiber, seed or oil yield; or low, legally allowed content of Δ^9-THC.

In breeding efforts to maintain monoecy in hemp, particular attention is paid to the negative selection of male flowers before pollination and to seed material quality control. However, the most important aspect of seed plantation is the establishment and maintenance of spatial isolation. For the 'elite' seed category, the spatial isolation level should be 5000 m, while for 'select' seed plantations, the requirement is 1000 m [20]. As reported by Faux [30], male plants commonly occur in contract 'select' seed plantations; hence the need for continued control and negative selection. In Poland, hemp cultivation is regulated by the Act on seed production of November 9, 2012 (Journal of Laws: Dz.U. 2012, item 1512) [34] which stipulates that in seed plantations producing 'elite' hemp seed material, the allowed number of male plants must not exceed 1 plant per 300 m^2, and for 'select' seed material –15 plants per 10m^2, according to Regulation of the Minister for Agriculture and Rural Development (Dz. U. 2013; 517) [35].

All breeding work on current and new varieties mainly focuses on maintaining the low hallucinogen content, high economic utility, and consistent monoecy of the variety.

Hemp cultivation in Europe is a centuries-old tradition. In a number of European states, including Great Britain, France, the Netherlands, Germany, Spain, and Italy, hemp was an important industrial crop from the Middle Ages until the end of the Age of Sail [36, 37]. In 1993–1996, cultivation of industrial hemp was legalized in most European Union member states. In 2011, the surface area of hemp cultures in Europe dropped to the lowest value since 1994 – approx. 8000 ha. An upward trend existed in the years 2012–2016, with the record high of 33,000 ha noted in 2016. As reported by the European Industrial Hemp Association [7], current surface area of industrial hemp cultures in Europe is the largest since World War II, and is estimated at close to 33,000 ha. Major cultures exist in France, the Netherlands, the Baltics, and Romania. However, as emphasized by Carus [36], before the collapse of the Soviet Union, the area was nearly 100,000 ha in Eastern Europe alone, with a major contribution from the Czech Republic. In 2011, the total area of hemp cultures globally was approx. 80,000 ha [38]. In recent years, a number of European countries either launched or expanded their hemp plantations, mainly to produce seeds for the health food market [7]. Countries where hemp plantation surface area first exceeded 1000 ha in 2014 included: the Netherlands (1462 ha) and Lithuania (1061 ha) [7]. According to EIHA reports [7], in 2014, France was the European leader in hemp seed production, with a crop area of 10,500 ha. Lekavicius *et al.* [39] pointed out that there was no consistent trend in hemp cultivation in many European countries, as demonstrated by statistics from France, where the crop area increased from 5400 ha to 11,300 ha in 2011. The 2014 hemp plantation area in European countries, based on EIHA data [7], is shown in Fig. 1. Data on Poland was adjusted based on current data from Institute of Natural Fibres and Medicinal Plants (INF&MP), collected from cultivation contracts.

area consistently decreased, falling down to 3500–6000 ha in 1987–1989. This continued reduction of hemp plantation area in Poland was both due to economic factors – the decreasing profitability of production led to closures of hemp processing plants [24] – and to cultural shifts associated with abuse of cannabis as an intoxicant. Lower demand for domestic hemp raw material was also associated with imports of cheap fibers from Asia [41]. In accordance with data from the General Agricultural Census, in 2001, hemp plantation area in Poland was less than 200 ha, and in 2002, as few as 71 hemp plantations existed, with a total sowing area of 83 ha. The plantation area further decreased to 80 ha in 2003. Most hemp plantations were located in Lublin and Lower Silesia provinces. Another reason for decreased interest in the hemp cultivation was the fact that it was particularly labor-intensive and poorly mechanized. A sharp increase was noted in 2004, when Poland joined the European Union. The crop became more attractive due to additional financial support, and its total surface area in Poland increased to 909.63 ha, according to the Polish Agency for Restructuring

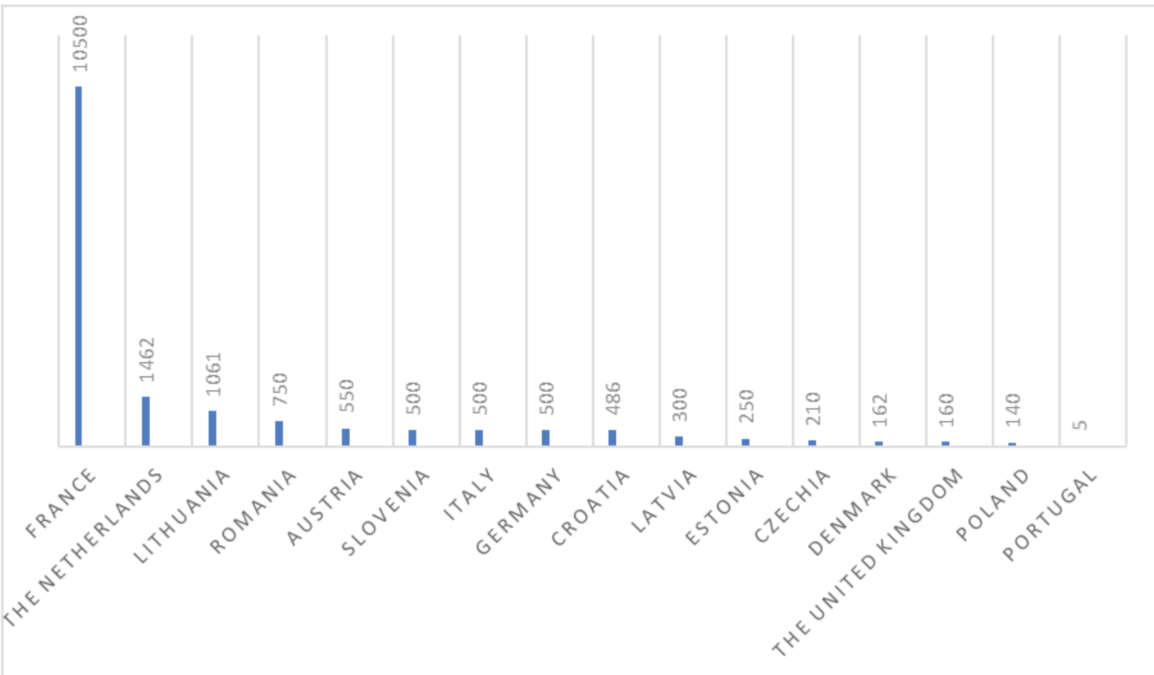

Figure 1

The 2014 hemp plantation area in European countries, based on EIHA data

In Poland, tradition of hemp cultivation dates back to the times before the Second World War. In 1920s and 1930s, hemp plantation surface area reached 29,000 ha [40]. In subsequent years, the

and Modernization of Agriculture [42]. Mańkowski [41] stated that the EU accession and launch of production by new contracting companies were factors associated with the record sowing area noted in the years 2006–2008. Sadly, subsequent years brought drops in the plantation areas, from nearly 950 ha in 2009 to 315 ha in 2013, to 140 ha in 2014 (data from INF&MP). Moreover, INF&MP data indicate that in 2016, Polish hemp plantation area was 808 ha, mainly contracted for straw, fiber, industrial seed, and food production. Moreover, in 2016, the area of hemp plantations for select seed material was only 160 ha. Considerably better was 2017, as total contracted hemp plantation area reached nearly 7000 ha (INF&MP), the highest in nearly thirty years. Sowing area reported to province authorities was as follows: the largest areas were planned in Warmia and Masuria (2,868.85 ha) and West Pomerania (874.12 ha) provinces, while the smallest – in the Lubuskie province (4.26 ha). The post-2015 increase of interest in hemp can mainly be attributed to EU financial support for fiber plant growers. Subsidies for hemp plantations were paid out in addition to area payments, in the amount of EUR 200/ha, though the final distribution of the entire funding depended on the number of hectares of industrial hemp that were contracted and submitted for direct subsidies [42].

POLISH MONOECIOUS VARIETIES OF INDUSTRIAL HEMP (*C. SATIVA* L.)

Currently, 8 Polish monoecious varieties of industrial hemp (*C. sativa*) are listed in the Common Catalogue of Varieties of Agricultural Plant Species (CCA) and the National Registry. Overall, CCA currently lists 57 industrial hemp varieties, most of which are monoecious. All industrial hemp varieties, both Polish and foreign, authorized for cultivation, contain only trace amounts of the psychoactive ingredients. In the EU, the maximum allowed content of these compounds is 0.2%. Six out of the 8 Polish varieties registered with the Polish Center for Cultivar Testing (COBORU) [43] have been bred in the INF&MP in Poznań: Białobrzeskie, Tygra, Wielkopolskie, Wojko, Rajan, and Henola [43]. Out of the remaining two, the Beniko variety was bred in the US, and Glyana was bred in Ukraine. The Wielkopolskie variety was bred in INF&MP, but in 2014 the property rights to this cultivar were transferred to Maria Kowalska and her "KOW-MAR Agricultural and Seed Holding" [43]. The oldest variety registered by COBORU (1967) [43] is Białobrzeskie. As reported by Jerzy Mańkowski *et al.* [44], the variety belongs to the Central-European type, and is perfectly suited to the weather and soil conditions of Poland. Grabowska *et al.* [45] found that the vegetation period of Białobrzeskie hemp is between 80 and 100 days, and that depending on the cultivation technology, the plants grow up to 250–350 cm tall. The seed yield from this variety is 1.48 $t \cdot ha^{-1}$, and the straw yield is stable at 10 $t \cdot ha^{-1}$. Breeding another monoecious variety took nearly 20 years. In 1985, a second *C. sativa* variety, Beniko, was registered in Poland. It had a vegetation period similar in length to that of Białobrzeskie, as well as a similar straw yield, but a considerably lower seed yield of approximately 0.9 $t \cdot ha^{-1}$ [44].

In 2007–2017, six more monoecious industrial hemp varieties were registered with COBORU [43]. They were as follows: Tygra (2007), Wielkopolskie (2009), Wojko (2011), Rajan (2014), and two varieties registered in 2017 – Henola and Glyana. Varieties of hemp grown at the INF&MP in Poznan with Institutes exclusive right to the variety granted by the COBORU are given in table 1.

After 2000, breeding work was based on cross-breeding between monoecious and dioecious hemp varieties. Tygra, a cross-breed between two monoecious varieties, took the least time to breed (INF&MP data). Each of the listed varieties had a distinctive trait, and in the case of Tygra, it was a considerably shorter vegetation period (by 1–2 weeks). In turn, the Wojko variety had a stable yield of seeds and straw and the highest total stem length [44]. In February 2014, another monoecious hemp variety was registered with COBORU [43] – Rajan, distinguished by its very high biomass yield with a high seed yield, which gives it great potential for use in energy production. Work on another variety, Henola, took 7 years, and was conducted in the INF&MP Experimental Facility in Pętkowo. Positive selection for lowest height, shortest growth period, and well-formed flowers resulted in a number of interesting lines, out of which the Henola line was found optimal [29]. In 2014, the Henola variety was submitted for registration tests. Vegetation period of its distinctive traits was decreased by approx. 50%, and had significantly larger flowers than those of Białobrzeskie variety [29]. It also has a significantly shorter stem, which contributes to considerably easier harvest in seed plantations [46]. Burczyk [29] reported that the seed yield from Henola variety is 4 times as high as the mean seed yields from other agricultural varieties of hemp registered in Poland. Therefore, the variety can be recommended for select seed plantations providing material for the extraction of cannabinoids (CBD, Δ^9-THC), used in the rapidly developing pharmaceutical industry, as well as for production of edible or medicinal oil. Other major uses listed by the author included the use of panicles for essential oil extraction, or the use of seeds as a biocomponent in biofuel production [29].

Due to both legal regulations and market demand, efforts have been made to breed varieties with a short growth period, a stable low content of Δ⁹-THC, and the highest possible content of CBD. Mańkowski *et al.* [44] emphasized that the monoecious varieties registered in Poland that contain less than 0.2% of Δ⁹-THC are important not only for their uses in a number of industries, but also for their breeding potential. The content of psychoactive Δ⁹-THC in hemp results from interactions between hereditary and environmental factors [47]. Polish and EU legislation provide no basis for restricting the plantation area of industrial hemp (*C. sativa*) that has a Δ⁹-THC content within the legal limits. In the coming years, hemp cultivation may become one of the most profitable agricultural activities, mainly due to the wide variety of possible uses for hemp products.

absolute amount of a nutrient that the plant accumulates throughout a given developmental stage, but rather by the minimum concentration of the nutrient required for the full performance of metabolic processes. As reported by Grabowska [40, 49] and Grabowska and Burczyk [24], optimally balanced supply of basic nutrients in $kg \cdot ha^{-1}$ is: 90–120 N, 70–100 P_2O_5, and 150–180 K_2O. According to the same authors, the N:P:K ratio should be 1:0.7:1.5 in hemp cultivated for fiber, and 1:0.8:1 in hemp cultivated for seeds. Hemp should be fertilized in early spring, approx. 2–3 weeks before the planned harvest time. Fertilizer dosage should be selected based on the site and planned use of the crop. Hemp is a good indicator of land quality [50] and tolerates both mineral and natural fertilizers (manure) very well [24]. According to Struik *et al.* [26], hemp is not very demanding in terms of fertilization, and its robust root system allows for effective use of soil nutrients [23, 52, 53]. Literature also points to the importance of appropriate variety selection in achieving the desired use characteristics. In their study on the impact of hemp variety on yield in three European states located at different latitudes (Italy, the Netherlands, and the United Kingdom), Struik *et al.* [26] reported the highest dry weight yields in Italy, lower ones in the Netherlands, and the lowest in the United Kingdom. At the same time, the authors claim that quality hemp fiber can be obtained in all of Europe. However, the appropriate agrotechnical parameters for a specific variety must be adjusted to the weather and soil conditions present at a specific latitude. The role of hemp variety is key not only due to its use parameters, but also due to the advances in biological knowledge that can be used to improve productivity [26].

Table 1

Varieties of hemp grown at the INF&MP in Poznań with Institutes exclusive right to the variety granted by the COBORU

Variety	Parents	Form of variety	Beginning of breeding work	Variety registration	Breeding duration [years]
Białobrzeskie	(LKCSD x Kompolti) x Fibrimon	(dioecious x monoecious) x monoecious	1956	1967	12
Beniko	Fibrimon 21 x Fibrimon 24	monoecious x monoecious	1964	1985	21
Tygra	Białobrzeskie x Ukraińskie	monoecious x monoecious	1998	2007	9
Wojko	Jermachowskie x Beniko	dioecious x monoecious	2000	2011	11
Rajan	Giganteus x Białobrzeskie	dioecious x monoecious	2000	2014	14
Henola	Zołotonowska 13 x Zenica	monoecious x dioecious	2004	2017	13

AGROTECHNICAL REQUIREMENTS OF HEMP

Macronutrient needs

The increasing interest in hemp cultivation necessitated an investigation into optimum agrotechnical conditions required for satisfactory yields with the desired parameters, in line with the specific purpose of cultivation. As seen in multiple research papers, studies on *C. sativa* mainly focus on finding the optimum dosage of nitrogen fertilizers, sowing depth, and harvest time. According to Grzebisz [48], plants require a specific supply of minerals to carry out their basic life processes (growth, development, and reproduction), which can be categorized in three aspects: quality, quantity, and critical demand time. Moreover, the author emphasizes that the nutritional needs of the plant are not expressed by the

Nitrogen. Nitrogen content in optimally nourished plants ranges between 0.5 and 7% [48], and the levels of this macronutrient at the critical growth stage have a decisive impact on the quantity and quality of product. Similarly to other plants, *C. sativa* requires nitrogen nearly at all times in the vegetation period [23]. However, the largest absorption is observed during the most intensive growth, i.e. the second month of the vegetation period [24]. Therefore, the soil levels of this element should be accurately determined, so as to adjust the additional nitrogen supply to the planned use of the crop. On latitudes and in the climate of Poland, the optimum levels of nitrogen fertilization range between 90 and 120 kg N·ha^{-1} [24, 49, 51, 54]. However, authors also emphasize that these amounts must be optimized based on a specific location, as the final effect largely depends on the macronutrient levels at the specific site selected for cultivation. Amaducci *et al.* [22] demonstrated that at nitrogen level of 100 kg·ha^{-1}, each additional kg of nitrogen supplied by fertilization increased the dry weight production by 20 kg. Vera *et al.* [55] compared the impact of nitrogen dosages in range of 40–120 kg N·ha^{-1}, and found a significant dose-response effect in terms of yield when soil levels of the nutrient available to the plants were low. In turn, Tang *et al.* [23] found a dose of 60 kg N·ha^{-1} sufficient, due to hemp's highly effective use of soil nitrogen. In their study of nitrogen dosage impact, Grabowska and Koziara [54] found the highest hemp straw yield at 80 kg N·ha^{-1}. In addition, the authors reported decreased fiber content in the stems with higher nitrogen doses. As to Aubin *et al.* [56], they obtained the highest biomass yield at a dose of 200 kg N·ha^{-1}, but reported 150 kg N·ha^{-1} as the optimum dose for a satisfactory seed and biomass yield. All cited authors acknowledge that the broad range of possible nitrogen dosages mainly results from different culture purposes and soil conditions, whereas any nitrogen fertilization is the most effective when soil moisture conditions are optimal for plant growth. Grabowska [49], Oleszak [46], Amaducci *et al.* [22] and Burczyk [29] also indicate that for optimum and economically sound production in acidic soil, supply of calcium at a dose of 1500–2000 q·ha^{-1} of CaO is also required. When both nitrogen dosage and sowing density increase, there is a rise in straw yield due to intense green weight growth [26, 54, 55]. Amaducci *et al.* [22] added that nitrogen dosed at above 120 kg N·ha^{-1} increases hemp biomass production, but at the cost of deteriorated fiber quality due to low cellulose content. These observations are corroborated by Baraniecki [51] and Tang *et al*. [23], who also pointed out that increasing nitrogen dosage decreases the seed yield, and therefore, in hemp cultivated for seed, nitrogen dosage should be lower and adjusted to other factors, such as the physical and chemical properties of the soil and the pioneer crop used. Finnan and Burke [57] and Tang *et al.* [23] report that the use of higher nitrogen doses affects hemp morphology, increasing its height and shoot diameter. Furthermore, Vera *et al.* [55] demonstrated that nitrogen may not only restrict the protein content in hemp seeds, but also significantly affect their oil content. In a study by Campiglia *et al.* [59], nitrogen fertilization in the dose range of 50–100 kg·ha^{-1} caused a higher stem yield, but did not significantly affect the yield of flowers and seeds. Overuse of nitrogen fertilization is an adverse factor in hemp cultivation, as it may cause morphological changes in the leaf blades making them vulnerable to pathogenic infestation [48]. The author also points out that excessive nitrogen dosage in any plant results in poorly formed mechanical tissue, which in turn causes lodging, making harvest more difficult. This is due to such effects of excessive nitrogen as extended vegetation period, increased straggling, and lower fiber content and quality, all of which leads to a lower long fiber yield, despite a higher yield of straw [48, 52, 54]. The study by Bocsa *et al.* [58] demonstrated a significant correlation between nitrogen dosage and Δ^9-THC content in leaves. The authors reported that leaf Δ^9-THC content in each part of the plant decreased with more nitrogen fertilization; the highest Δ^9-THC levels were found in the leaves near the top of the shoot and branches, and the lowest in the oldest leaves of the plant.

Phosphorus. Phosphorus content in well-nourished plants ranges between 0.1 and 1.0%, and a phosphorus deficiency is considered to occur at levels below 0.1% [48]. According to Grabowska and Burczyk [24], optimum phosphorus dosage for hemp ranges between 70–100 kg P_2O_5·ha^{-1}. As the authors report, phosphorus actively contributes to seed formation and maturation. Hemp absorbs phosphorus throughout the vegetation period, though most intensively at the flowering and seed filling stages, thus contributing to higher seed weight. As reported by Vera *et al.* [55], increasing phosphorus doses during fertilization does not impact the content of protein and oil in hemp seeds, but may significantly increase their weight. Also Aubin *et al.* [56] confirm the limited impact of phosphorus on seed composition and biomass production in hemp.

Potassium. Potassium is a macronutrient that is most needed at the stage of greatest biomass growth [48]. Grabowska and Burczyk [24] state that this is the most valuable macronutrient in terms of fibrous plant development, as it contributes to the production of high-quality fiber. In literature, the optimum levels of potassium fertilization in hemp are reported at 150–180 kg $K_2O \cdot ha^{-1}$. Hemp absorbs the element throughout its vegetation period, and authors report most intense intake as flowering starts, which coincides with the start of fiber formation in the stem. Finnan and Burke [57] reported that most potassium absorbed by hemp (70–75%) is accumulated in the stem. They also added that hemp has a lower potassium demand than other crops. Aubin *et al.* [56] confirmed that potassium fertilization has no impact on the biomass or seed yield from hemp cultures, and therefore one may assume that fertilization with this element would bring no industrial benefits in hemp cultures on soils with high initial potassium levels. However, according to Grzebisz [48], optimum access to this macronutrient may be very important for the plants, as it minimizes the impact of stress factors that deteriorate the yielding potential and the quality of yield.

Calcium. Calcium is a macronutrient that improves the physical and chemical properties of soil and stimulates the development of soil fauna and flora. In acidic soils, phosphorus is not easily absorbable, and therefore liming may increase phosphorus absorption by plants. The optimum dosage of calcium in acidic soils ranges between 1500 and 2000 $kg \cdot ha^{-1}$ of CaO [24]. In Poland, nearly half of agriculturally used soils are acidic or highly acidic [60]. In acidic soils (pH<5), liming is mandatory; a recommended treatment is applying lime with magnesium during first tillage or winter tillage, at a dose of 1500 $kg \cdot ha^{-1}$ of CaO in lighter soils, and 2000 $kg \cdot ha^{-1}$ of CaO in heavier sols. In soils with a pH or 5.1–6.0, liming is indicated [50, 51]. Also Grabowska and Koziara [54] emphasize that application of calcium oxide contributes to better use of mineral fertilizers by hemp.

Choice of soil, pioneer crop, and field preparation

Over centuries, hemp spread globally, adapting to variable environmental conditions. Due to this adaptation to a range of weather and soil conditions, hemp can be classified into either the northern type, which is a dwarf type with a short vegetation period, or the southern type, tall-growing with a long vegetation period [25, 26]. Bocsa and Carus [52] identified two additional ecological types of hemp: Asiatic and Central European.

One of the most important factors that guarantee a satisfactory yield in line with the purpose of cultivation, is soil selection. Hemp is typically associated with lowlands and river valleys, and can be grown in mineral and peat soils. The optimal soil is fertile; rich in humus, nitrogen, and calcium; with a neutral or slightly alkaline pH – optimum pH values range between 7.1 and 7.6 [25]. INF&MP guidelines recommend against using sites with a pH below 6.0. The soil should also have high air permeability and good water retention, without crust. Depth to the water table should be at least 80 cm.

According to Grabowska [49], hemp can be also cultivated on high quality loess soils, while light and sandy or heavy loamy soils should be avoided. Other unsuitable sites include permanently wet lands with unregulated water conditions [24, 26, 49]. In his study on the Białobrzeskie variety, Baraniecki [51] obtained the highest seed yield on chernozem and rendzina soils with a neutral pH, and the highest straw yield – on acidic brown earth soils. Research on Poland's weather and soil conditions and hemp's requirements in this regard, performed by INF&MP in Poznań, demonstrated that the crop can be grown nearly everywhere in the country, including many areas with valuable natural assets [24, 25]. With appropriate soil fertility and good fertilization, hemp can be grown in monoculture. For several years (3 years recommended) it can be grown continuously with no yield losses (for fiber production), though in this setting, fertilizer dosages should be increased. However, hemp monoculture may be associated with a lower yielding potential, as well as with increased vulnerability to parasites and diseases such as hemp canker or damping-off [20, 25]. In line with INF&MP guidelines, suitable pioneer crops for hemp include: root crops, perennial legumes (alfalfa, clover, pea, vetch, field peas), and cereals. In turn, hemp is an excellent pioneer crop for all plants, and for cereals in particular – it may increase the grain yield of winter wheat by approx. 20% [25]. In the case of hemp cultures for select seed material production, monoculture is not allowed by the Act on seed production of November 9, 2012 (as amended). Hemp is also suitable for use in the reclamation of land degraded by mining, as it can absorb heavy metals such as cadmium, lead, zinc, and copper from contaminated soil, contributing to its rehabilitation [41, 61].

Preparation of fields for hemp crops should follow good agricultural practice. The primary agrotechnical procedure for hemp cultures is deep autumn tillage (approx. 25–30 cm), leaving sharp ridges, so as to facilitate the storage of water from winter precipitation [46]. Springtime procedures should be limited to loosening and leveling the topsoil, applying the appropriate mineral fertilizers, elimination of germinating weeds, and most importantly, maintaining the granular structure of the soil [49, 50]. According to Grabowska [40], hemp can also be grown in farms using simplified agricultural methods, i.e. no-till farming.

Cierpucha [20] explains that hemp cultures established in line with good agricultural practice do not require chemical pest or disease control. The author also reports that herbicide sprays with linuron in a dose of 1–1.2 $kg \cdot ha^{-1}$ per 300 l of water may be used immediately after sowing for prevention.

During preparation of a site for hemp culture, one must determine its purpose (fiber, biomass, or seed production) to optimize the agrotechnical parameters, and consider a number of interacting factors, such as: hemp variety, sowing time, sowing density [29, 62, 63], soil type and nutrient content, fertilization, pioneer crop, and weather conditions – precipitation, temperature, and solar exposure, so as to obtain a satisfactory, profitable yield [26, 49, 51].

Sowing time and density

Optimal sowing timing is a key factor in hemp cultivation, and largely depends on springtime weather conditions. In Poland, hemp sowing time depends on the planned location of the plantation. In southern Poland, the best time for sowing hemp typically includes early-to-mid April; in central Poland, it occurs later, in mid-to-late April, while in northern Poland, it is extended until mid-May [25]. Cierpucha [20] adds that the appropriate sowing time depends on stable air temperature at 8–10°C, as warmer soil guarantees rapid and equal sprouting. This is corroborated by Zadrożniak *et al.* [25] who reported that sowing hemp in cold soil causes excessively long germination and a larger percentage of atrophied plants. Late sowing, in turn, shortens the vegetation period, which directly contributes to lower yield quantity and quality [24, 50]. Hemp sowing density determines its use characteristics, as Zadrożniak *et al.* [25] reported that the number of plants per unit of surface is a fundamental factor for productivity, fiber quality, and seed yield. According to Cierpucha [20] and Amaducci *et al.* [53], optimum hemp sowing depth is 3–4 cm. Multiple studies [20, 25, 40, 50] indicate that the optimum sowing density for a seed plantation should be 10–15 $kg \cdot ha^{-1}$, or approx. 60 germinating plants per 1 m^2, while for industrial plantations, the density depends on the purpose, and should range between 40 and 70 $kg \cdot ha^{-1}$. In plantations for biocomposite production, sowing density should be 30–40 $kg \cdot ha^{-1}$, and for fiber production, 60–70 $kg \cdot ha^{-1}$. Furthermore, Hall *et al.* [21] report that there is no benefit to exceeding the density of 80 $kg \cdot ha^{-1}$, as the difference in final yield is insignificant. The authors also add that higher sowing densities result in longer and thinner hemp stems, with a higher fiber content.

According to Cierpucha [20], the correct sowing timing results in sprouting after 8–10 days, so that the hemp quickly covers the spaces between rows, and competes better with weeds. Hall *et al.* [21] noted that increasing the density from 100 to 200 plants per 1 m^2 significantly restricted weed growth (from 23.2 to 6.5 $g \cdot m^2$), while increases to 300 and 400 plants per 1 m^2 caused further decreases, to 2.6 and 1.5 $g \cdot m^2$, respectively.

Row spacing is a very important aspect of hemp sowing. In plantations for select seed material production, it should be 50–60 cm, while in industrial plantations, spacing of 7.5–15 cm is commonly used. The Act on seed production of November 9, 2012 (as amended) only prescribes row spacing for select seed material production, and the recommended spacing allows for precise negative selection of male plants in the flowering period. This regulation also facilitates field inspections of hemp plantations for seed production.

Cannabis sativa L. harvest time

The distinctive morphological features of hemp include its considerable height and its thick, hard, fibrous stem. Hemp also has a relatively high green weight production [20]. Zadrożniak *et al.* [25] report that, depending on vegetation time and conditions, the plants may grow 1.0–5.0 m tall. The authors also point out that the stem height, which depends on the specific variety and the planting density, determines straw yield. Hemp biometric parameters are a source of many complications during harvest, hence the strict requirements regarding machines for hemp harvesting. Late harvest in seed plantations causes seed shattering and potential losses from bird feeding. Depending on the purpose of cultivation, hemp is typically harvested in late August or in September [24]. As reported by Zadrożniak *et al.* [25], in seed plantations, hemp should optimally be harvested upon the maturation of seeds in the mid-portion of the panicle. This approach gives the best quality seed material. In industrial plantation, this timing of harvest guarantees the highest fiber yield, but lower quality seed. High yields of strong fibers are most likely when harvest takes place 1–2 weeks after the end of flowering.

Water conditions

Hemp development is not even throughout the vegetation period, as three-quarters of green weight grow between the development of flower buds and the end of flowering. The period of intense fiber development is very short, lasting approx. 40 days, and begins at the early stage of seed maturation [20]. Multiple studies indicate that the course of weather conditions has a decisive impact on the quantity and quality of fiber, as well as on the seed yield. According to Grabowska and Koziara [64], adequate availability of soil moisture has a much larger impact on hemp growth than precipitation. Zadrożniak *et al.* [25] reports that hemp development is affected not only by total precipitation, but also by its distribution throughout the vegetation period, as water demand is strictly correlated with growth intensity, and therefore, most water is needed during intense stem growth. Amaducci *et al.* [53], Cierpucha [20] and Zadrożniak *et al.* [25] report that hemp has a well-developed root system that can reach a depth of 2–3 m. The root morphology of hemp facilitates the absorption of water from deeper soil layers, which allows it to survive the stress conditions associated with drought.

As reported by Grabowska and Koziara [63], the occurrence of short dry spells during vegetation resulted in significantly lower yield, ranging between 7 and 8 $t \cdot ha^{-1}$, though dry conditions at the early stage of plant development did not have a significant impact on yield. Optimal precipitation in the vegetation period, ensuring normal growth and development, is 250–300 mm [20, 24, 25, 40]. Despite its high transpiration coefficient, hemp is adversely affected by excessively high groundwater levels, and especially by prolonged water-logging [26]. Baraniecki [51] demonstrated a negative correlation between high precipitation during sowing and vegetation, and weight per thousand seeds.

Heat and light requirements of hemp

Heat requirements of hemp largely depend on its type. The Central-European hemp grown in Poland belongs to the intermediate type. Literature indicates that the heat requirements of *C. sativa*, similarly to its water requirements, are high, and that hemp is considered as a thermophilic plant [20, 25, 40, 51]. Good solar exposure and optimum temperature are necessary for the proper growth and development of the plants. For a vegetation period of 120–150 days, the total heat supply optimal for seed maturation is 2000–3000°C, Zadrożniak *et al.* [25] add that at latitudes between 51° and 58°, the total heat supply during hemp vegetation period should be between 2000 and 2600°C. In turn, the heat requirements of hemp between sprouting and technical maturity, range between 1900 and 2000°C. To reach biological maturity, hemp requires a total heat supply of 2700–3000°C. Seed germination begins when soil temperature exceeds 8–10°C [40]. When the soil is well heated, hemp sprouts within 8–12 days. When the plant reaches 4–5 pairs of leaves, it can survive short-term frost of up to –7°C, but development stops until favorable weather conditions return [20, 40, 46]. Grabowska and Burczyk [24] emphasize that sowing in cold soil results in late germination and increased weed growth. The study on hemp by Baraniecki [51] indicates that high temperatures in April, i.e. in the sowing and sprouting period, are positively correlated with straw and seed yields.

Multiple publications demonstrate that *C. sativa* benefits the most from higher temperatures during the most intensive growth, i.e. in June and July. Low temperatures and low precipitation at this time inhibit hemp growth, leading to lower quantity and quality of straw, fiber, and seeds. According to Baraniecki [51], high temperatures throughout the entire vegetation period guarantee high hemp straw and seed yields. Hemp is considered a short-day plant [20, 26, 65]. As reported by Grabowska [40, 64] and Cierpucha [20], based on thermal conditions and day length, the southern regions of Poland, such as the Lower Silesia and Lublin provinces, are most suitable for hemp seed plantations.

Ethical approval: The conducted research is not related to either human or animal use.

Conflicts of interest: The authors declare no conflicts of interest.

ACKNOWLEDGMENT

This research was carried out within the framework of a research project No. INNOMED/I/11/NCBR/2014 financed by the National Centre for Research and Development.

REFERENCES

1. Grotenhermen F. Reassessing the drug potential of industrial hemp. Nova Institut, Huerth 2002:1-48.

2. Merlin MD. Archeological evidence for the tradition of psychoactive plant use in the old world. Econ Bot 2003; 57(3):295-323. doi: http://dx.doi.org/www.jstor.org/stable/4256701

3. De Backer B, Debrus B, Lebrun P, Theunis L, Dubois N, Decock L, et al. Innovative development and validation of an HPLC/DAD method for the qualitative and quantitative determination of major cannabinoids in cannabis plant material. J Chromatogr B 2009; 877(32):4115-4124.

4. Fleming MP, Clarke RC. Physical evidence for the antiquity of *Cannabis sativa* L. (*Cannabaceae*). J International Hemp Assoc 1998; 5(2):80-92.

5. Burney DA. Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. Hum Ecol 1997; 25(3):437-457.

6. Aguilar S, Gutiérrez V, Sánchez L, Nougier M. Medicinal cannabis policies and practices around the world. IDPC Publication 2018:1-27. Available at: https://idpc.net/publications/2018/04/medicinal-cannabis-policies-and-practices-around-the-world (accessed: 29.04.2019)

7. EIHA. European Industrial Hemp Association, http://www eiha.com (accessed: 25.02.2019).

8. Pacifico D, Miselli F, Carboni A, Moschella A, Mandolino G. Time course of cannabinoid accumulation and chemotype development during the growth of *Cannabis sativa* L. Euphytica 2007; 160:231-240. doi: http://dx.doi.org/10.1007/s10681-007-9543-y

9. Truta E, Surdu S, Rosu CM, Asaftei M. Hemp – biochemical diversity and multiple uses. Sectiunea Genetica si Biologie Moleculara 2009; 10:1-8.

10. Izzo AA, Borrelli F, Capasso R, Di Marzo V, Mechoulam R. Non-psychotropic plant cannabinoids: new therapeutic opportunities from an ancient herb. Trends Pharmacol Sci 2009; 30:515-527. doi: http://dx.doi.org/10.1016/j.tips.2009.07.006

11. Russo EB. Taming THC: potential cannabis synergy and phytocannabinoidterpenoid entourage effects. Br J Pharmacol 2011; 163:1344-1364. doi: http://dx.doi.org/10.1111/j.1476-5381.2011.01238.x

12. Russo EB, Guy GW. A tale of two cannabinoids: The therapeutic rationale for combining tetrahydrocannabinol and kannabidiol. Med Hypotheses 2006; 66:234-246. doi: http://dx.doi.org/10.1016/j.mehy.2005.08.026

13. Vemuri VK, Makriyannis A. Medicinal chemistry of cannabinoids. Clin Pharmacol Ther 2015; 97(6):553-558. doi: http://dx.doi.org/10.1002/cpt.115

14. Peiretti PG. Influence of the growth stage of hemp (*Cannabis sativa* L.) on fatty acid content, chemical composition and gross energy. Agric J 2009; 4(1):27-31. doi: http://dx.doi.org/10.3923/aj.2009.27.31

15. Schwarz I, Kovačević S. Textile application: from need to imagination. Intech Open 2017:1-27. doi: http://dx.doi.org/10.5772/intechopen.68376

16. Mańkowski J, Kubacki A, Kołodziej J. Materiały budowlane na bazie paździerzy konopnych i spoiwa wapiennego. PILIK – Biuletyn Polskiej Izby Lnu i Konopi 2011; 16:29-33. [in Polish].

17. Andre CM, Hausman JF, Guerriero G. *Cannabis sativa:* the plant of the thousand and one molecules. Front Plant Sci 2016; 7(19):1-17. doi: http://dx.doi. org/10.3389/fpls.2016.00019

18. Marsh G. Next step for automotive materials. Mater Today 2003; 6:36-43. doi: http://dx.doi.org/10.1016/S1369-7021(03)00429-2

19. Mouthuy PA, Zargar N, Hakimi O, Lostis E, Carr A. Fabrication of continuous electrospun filaments with potential for use as medical fibres. Biofabrication 2015; 7(2):1-13. doi: http://dx.doi.org/10.1088/1758-5090/7/2/025006

20. Cierpucha W. Technologia uprawy i przetwórstwa konopi włóknistych, Nowa metoda rekultywacji terenów zdegradowanych w rejonie Kopalni Węgla

Brunatnego (KWB) Konin z zastosowaniem uprawy konopi włóknistych [Technology of cultivation and processing of hemp, New method of reclamation of degraded land in the area of Brown Coal Mine in Konin with application of hemp cultivation]. LIFE11ENV/PL/445: 2013:12-31.

21. Hall J, Bhattarai SP, Midmore DJ. Effect of industrial hemp (*Cannabis sativa* L.) planting density on weed suppression, crop growth, physiological responses, and fiber yield in the subtropics. Renewable Biores 2014; 2:1-7. doi: http://dx.doi.org/10.7243/2052-6237-2-1

22. Amaducci S, Errani M, Venturi G. Response of hemp to plant population and nitrogen fertilisation. Ital J Agron 2002; 6:103-111.

23. Tang K, Struik PC, Yin X, Calzolari D, Musio S, Thouminot C, et al. A comprehensive study of planting density and nitrogen fertilization effect on dual-purpose hemp (*Cannabis sativa* L.) cultivation. Ind Crops Prod 2017; 107: 427-438. doi: http://dx.doi.org/10.1016/j.indcrop.2017.06.033

24. Grabowska L, Burczyk H. Wybrane zagadnienia z uprawy konopi włóknistych w Polsce [Selected aspects of hemp cultivation in Poland]. Zagadnienia Doradztwa Rolniczego 2005; 4:121-127.

25. Zadrożniak B, Radwańska K, Baranowska A, Mystkowska I. Possibility of industrial hemp cultivation in areas of high nature value. Ec Reg Studies 2017; 10(1):114-127.

26. Struik PC, Amaducci S, Bullard MJ, Stutterheim NC, Venturi G, Cromack HT. Agronomy of fiber hemp (*Cannabis sativa* L.) in Europe. Ind Crops Prod 2000; 11:107-118. doi: http://dx.doi.org/10.1016/S0926-6690(99)00048-5

27. Mediavilla V, Bassetti P, Leupin M, Mosimann E. Agronomic characteristics of some hemp genotypes. J Intern Hemp Assoc 1999; 6(2)45:48-53.

28. Grabowska L. Hodowla i nasiennictwo konopi włóknistych w Instytucie Włókien Naturalnych i Roślin Zielarskich w Poznaniu [Breeding and seeding of hemp at the Institute of Natural Fibres & Medicinal Plants in Poznań. Breeding and seeding of hemp]. Hodowla Roślin i Nasiennictwo 2009; 4: 38-40. [in Polish].

29. Burczyk H. Konopie oleiste (*Cannabis sativa* L. var. *oleifera*) uprawiane na nasiona do produkcji oleju i biogazu. [Oilseed hemp cultivars (*Cannabis sativa* L. var. *oleifera*) grown for oil and biogas]. Problemy Inżynierii Rolniczej 2016; 4(94):109-116. [in Polish]

30. Faux AM. Quantitative approach of the genetic determinism of sex expression in monoecious hemp (*Cannabis sativa* L.), and its relationship with flowering phenology and stem and seed yields. Dissertation. Université Catholique de Louvain Earth and Life Institute 2014:109-138.

31. Brook G, Liljefors K, Brook D, Stewart A. National industrial hemp strategy, Manitoba Agriculture, Food and Rural Initiative Agriculture and Agri-Food Canada, Ottawa 2008:1-8. Available at: http://compositesinnovation.ca/biofibre_reports/07-020-09.pdf (accessed: 20.01.2019)

32. Mandolino G, Carboni A, Forapani S, Faeti V Ranalli P. Identification of DNA markers linked to the male sex in dioecious hemp (*Cannabis sativa* L.). Theor Appl Genet 1999; 98:86-92.

33. Wielgus K, Luwańska A, Lassociński W, Kaczmarek Z. Estimation of *Cannabis sativa* L. tissue culture conditions essential for callus induction and plant regeneration. J Nat Fibres 2008; 5(3):199-207.

34. Ustawa z dnia 9 listopada 2012 r. o nasiennictwie. Dz.U. 2012 poz. 1512. 1-120. [in Polish]

35. Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 18 kwietnia 2013 r. w sprawie terminów składania wniosków o dokonanie oceny polowej materiału siewnego poszczególnych grup roślin lub gatunków roślin rolniczych i warzywnych oraz szczegółowych wymagań w zakresie wytwarzania i jakości materiału siewnego tych roślin. Dz.U. 2013 poz. 517. 1-99. [in Polish]

36. Carus M. European hemp industry 2001 till 2004: Cultivation, raw materials, products and trends. European Industrial Hemp Association (EIHA) 2005:1-11. Available at: http://news.bio-based.eu/media/news-images/20050309-09/05-02%20EU-EIHA%20e.pdf (accessed: 20.01.2019)

37. Carus M, Karst S, Kauffmann A, Hobson J, Bertucelli S. The European Hemp Industry: Cultivation, processing and applications for fibres, shivs, seeds and flowers. European Industrial

Hemp Association (EIHA) 2013:1-9. Available at: https://www.votehemp.com/wp-content/uploads/2018/09/13-03_European_Hemp_Industry.pdf (accessed: 20.01.2019)

38. Barth M, Carus M. Carbon footprint and sustainability of different natural fibers for biocomposites and insulation material study providing data for the automotive and insulation industry. Multihemp Carbon Footprint Natural Fibres 2015:1-48.

39. Lekavicius V, Shipkovs P, Ivanovs S, Rucins A. Thermo-insulation properties of hemp-based products. Latv J Phys Tech Sci 2015; 1:38-51. doi: http://dx.doi.org/10.1515/lpts-2015-0004

40. Grabowska L. Perspektywy uprawy konopi przemysłowych w Polsce. Monografia. Rola infrastruktury i techniki w zrównoważonym rozwoju rolnictwa. [Outlook for hemp cultivation in Poland. Monography. The role of infrastructure and technology in the sustainable development of agriculture]. IBMER, Warszawa 2005:193-200. [in Polish]

41. Mańkowski J. Wpływ metod roszenia na ilość i jakość jednopostaciowego włókna lnianego [Effect of retting methods on the quantity and quality of flax fiber]. Fragm Agron 2014; 31(2):46-55. [in Polish]

42. Acreage of hemp cultivars in Poland. ARiMR. Agencji Restrukturyzacji i Modernizacji Rolnictwa ARiMR. Available at: http://www.arimr.gov.pl/ (accessed: 25.01.2019) [in Polish].

43. Polish hemp cultivares. COBORU. Witryna internetowa Centralnego Ośrodka Badań Odmian Roślin Uprawnych – COBORU, http://www.coboru.pl. (accessed: 25.02.2019).

44. Mańkowski J, Kołodziej J, Zachwieja J. Przewidywany potencjał uprawy konopi włóknistych w Polsce w roku 2017 [The expected potential for fiber hemp cultivation in Poland in 2017]. Biuletyn Polskiej Izby Lnu i Konopi – PILIK 2017; 29:2-9.

45. Grabowska L, Jaranowska B, Baraniecki P, Tymków J. The results of hemp breeding in Poland. Natural Fibres, Special Edition 1998; 2:103-109.

46. Oleszak G. A może konopie. Tygodnik Rolniczy 2009; 35:28-29.

47. Kurhański M, Chrostowska-Kurhańska G. The factors influencing the content of cannabinoids in hemp. Natural Fibres 1995; 31:87-90.

48. Grzebisz W. Nawożenie roślin uprawnych [Fertilization of crops]. Powszechne Wydawnictwo Rolnicze i Leśne, Warszawa 2008; 16:156-261.

49. Grabowska L. Wpływ warunków siedliskowych i agrotechnicznych na wzrost, rozwój i plonowanie konopi. [The influence of habitat and agrotechnical conditions on the growth, development and yielding of hemp]. Ph.D. dissertation. Institute of Natural Fibres and Medicinal Plants, Poznań 2000, pp. 69. [in Polish]

50. Rębarz M. Konopie. Rośliny przemysłowe. Produkcja roślinna 2009; 3: 280- 288. [in Polish]

51. Baraniecki P. Plonowanie konopi siewnych (*Cannabis sativa* L.) w zależności od czynników siedliskowych i agrotechnicznych [Yield of hemp (*Cannabis sativa* L.) depending on habitat and agrotechnical factors]. Ph.D. dissertation. Institute of Natural Fibres and Medicinal Plants, Poznań 2014, pp. 82. [in Polish]

52. Bocsa I, Carus M. The cultivation of hemp. Botany, varieties, cultivation and harvesting. Hemptech, Sebastopol, CA, 1998: 1-176.

53. Amaducci S, Zatta A, Raffanini M, Venturi G. Characterization of hemp (*Cannabis sativa* L.) roots under different growing conditions. Plant Soil 2008a; 313:227-235. doi: http://dx.doi.org/10.1007/s11104-008-9695-0

54. Grabowska L, Koziara W. The effect of nitrogen dose, sowing density and time of harvest on development and yields of hemp cultivar Bialobrzeskie. J Nat Fibers 2005; 2(4):1-17. doi: http://dx.doi. org/10.1300/J395v02n04_01

55. Vera CL, Malhi SS, Raney JP, Wang ZH. The effect of N and P fertilization on growth, seed yield and quality of industrial hemp in the Parkland region of Saskatchewan. Can J Plant Sci 2004; 84(4):939-947. doi: http://dx.doi. org/10.4141/P04-022

56. Aubin MP, Seguin P, Vanasse A, Tremblay GF, Arif FM, Jean-Benoit Ch. Industrial hemp response to nitrogen, phosphorus, and potassium fertilization. Crop, Forage & Turfgrass Management 2015; 1(1):1-10. doi: http://dx.doi.org/10.2134/cftm2015.0159

57. Finnan J, Burke B. Potassium fertilization of hemp (*Cannabis sativa*). Ind Crops Prod 2013; (41): 419-422. doi: http://dx.doi.org/10.1016/j.indcrop.2012.04.055

58. Bocsa I, Máthé P, Hangyel L. Effect of nitrogen on tetrahydrocannabinol (THC) content in hemp *(Cannabis sativa* L.) leaves at different positions. J Int Hemp Assoc 1997; 4(2):78-79.

59. Campiglia E, Radicetti E, Mancinelli R. Plant density and nitrogen fertilization affect agronomic performance of industrial hemp (*Cannabis sativa* L.) in Mediterranean environment. Ind Crops Prod 2017; 100:246-254. doi: http://dx.doi.org/10.1016/j.indcrop.2017.02.022

60. Bednarek W, Reszka R. Wpływ wapnowania i nawożenia różnymi formami azotu. [Effect of liming and fertilization with various forms of nitrogen]. Annales Universitatis Mariae Curie-Skłodowska Lublin – Polonia 2007;62(1):69-76. [in Polish]

61. Mańkowski J, Kubacki A, Kołodziej J, Baraniecki P, Pniewska I. Rekultywacja terenów zdegradowanych w wyniku działania kopalni odkrywkowych [Reclamation of land degraded due opencast mines]. PILIK- Biuletyn Polskiej Izby Lnu i Konopi 2013a; 20: 7-10. [in Polish]

62. Burczyk H, Grabowska L, Strybe M, Konczewicz W. Effect of sowing density and date of harvest on biomass, straw, panicle, seed, cellulose and fiber yield of industrial hemp. J Nat Fibers 2009; 6:115-126. doi: http://dx.doi.org/10.1080/1544047OL)02972588

63. Burczyk H, Grabowska L, Kołodziej J, Strybe M. Industrial hemp as a raw material for energy production. J Industrial Hemp 2008; 13(1):37-48. doi: http://dx.doi. org/10.1080/15377880801898717

64. Grabowska L, Koziara W. Wpływ temperatury i opadów na plonowanie konopi włóknistych odm. Białobrzeskie [Influence of temperature and precipitation on the yield of hemp var. Białobrzeskie]. Natural Fibres 2001; 45:7-17.

65. Amaducci S, Zatta A, Pelatti F, Venturi G. Influence of agronomic factors on yield and quality of hemp (*Cannabis sativa* L.) fiber and implication for an innovative production system. Field Crops Res 2008b; 107:161-169. doi: http://dx.doi.org/10.1016/j.fcr.2008.02.002