PAN POLSKA AKADEMIA NAUK
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.156036
2025, No. 67 (X–XII): 16–29

A study on *Cannabis sativa* L. cultivated on loamy and sandy soils in north-eastern Poland

Krystyna Żuk-Gołaszewska[1], Barbara Kalisz*[2], Marian Lewicki[3], Hazem M. Kalaji[4], Robert Duliński[5], Janusz Gołaszewski[6]

[1] University of Warmia and Mazury, Faculty of Agriculture and Forestry, Department of Agrotechnology and Agribusiness, Pl. Łódzki 3, 10-727 Olsztyn, Poland

[2] University of Warmia and Mazury in, Faculty of Agriculture and Forestry, Department of Soil Science and Microbiology, Pl. Łódzki 3, 10-727 Olsztyn, Poland

[3] Linowiec 23, 13-324 Grodziczno, Poland

[4] Warsaw University of Life Sciences SGGW, Department of Plant Physiology, Institute of Biology, Nowoursynowska St, 159, bldg 37, 02-776 Warsaw, Poland

[5] University of Agriculture in Krakow, Faculty of Food Technology, Department of Biotechnology and General Food Technology, Balicka St, 122, 30-149 Kraków, Poland

[6] University of Lomza, Faculty of Health Sciences, Akademicka St, 14, 18-400 Łomża, Poland

* Corresponding author

RECEIVED 18.12.2024 ACCEPTED 18.06.2025 AVAILABLE ONLINE 29.10.2025

Highlights

- Loamy soil increases *Cannabis sativa* growth 2.5-fold vs. sandy soil
- Nitrogen fertilisation raises photosynthetic rate and leaf greenness index
- Silicon improves soil cation exchange, aiding *C. sativa* growth on sandy soil
- Water use efficiency and leaf area index are higher in loamy soil conditions

Abstract: The gradual implementation of legal regulations concerning sustainable agriculture, including the cultivation and use of *Cannabis sativa* L., in the European Union has heightened interest in this plant species among agricultural producers. This research presents the results of an on-farm field experiment conducted in north-eastern Poland to evaluate the growth, yield and physiological characteristics of *Cannabis sativa* L. in response to different soil conditions (loamy and sandy soils) and agronomic factors (sowing density, nitrogen fertilisation, and silicon application). *C. sativa* cultivated on loamy soil exhibited significantly greater growth and yield than on sandy soil, even without fertiliser application. However, sustained production would require nutrient replenishment in subsequent growing cycles. Nitrogen fertilisation increased photosynthetic rate, SPAD (leaf greenness index), and leaf area index (*LAI*), especially on sandy soil. However, its impact on final yield components (plant height, inflorescence length, dried mass) was minor compared to soil type. Nitrogen significantly boosted photosynthetic activity and chlorophyll content (SPAD), particularly at early growth stages. The data indicate that *C. sativa* can be successfully cultivated on both loamy and sandy soils, but agronomic interventions (silicon and nitrogen applications) are particularly beneficial for sandy soils. In this study, the plants also outcompeted the weeds to such an extent that herbicide application was unnecessary.

Hence, *cannabis* can be considered a low-to-moderate input crop, and can contribute to sustainable alternative agriculture. It is recommended to repeat the present study at a larger scale over a longer term to assess the economic, environmental effects, and after-effects on crop rotation of *C. sativa* cultivation.

Keywords: hemp, leaf area index (*LAI*), N and Si fertilisation, photosynthesis, SPAD

INTRODUCTION

Cannabis sativa L. is an environmentally friendly alternative crop with low fertiliser requirements. Due to its rapid growth and high competitiveness against weeds, *C. sativa* effectively reduces weed biomass without the use of herbicides (Bócsa and Karus, 1998; Żuk-Gołaszewska and Gołaszewski, 2018). This multipurpose crop has various applications in the production of food (flowers, seeds), biofuel (oil), and fibre (stems), as well as medicinal applications (cannabinoids) (Rupasinghe *et al.*, 2020; Zdaniewicz *et al.*, 2024).

Cannabis sativa is mostly grown under field conditions worldwide. In Europe, field-grown *Cannabis* is primarily used for industrial and pharmaceutical purposes, and usually, the seeds should be obtained from certified sources to ensure that the cultivated plants produce only female flowers. Male *Cannabis* plants are typically identified and removed during the flowering stage to prevent them from pollinating female plants. Pollinated flowering female plants shift their energy from producing cannabinoid-rich, resinous buds to producing seeds. The pollination results in lower cannabinoid content (such as THC – tetrahydrocannabinol and CBD – cannabidiol), smaller and less potent buds, and reduced overall yield. By eliminating male plants, growers can ensure that female plants remain unpollinated and produce larger, more resinous flowers with significantly higher concentrations of cannabinoids, making them more desirable for medicinal and recreational use. Removing male plants is a standard practice to maximise both the quality and potency of the harvest by encouraging female plants to focus their resources on cannabinoid and resin production rather than seed formation (Lipson Feder *et al.*, 2021; Kim *et al.*, 2024). The length of the growing season for hemp cultivars varies across climate zones and is closely correlated with flowering and harvesting dates. Early-sown *Cannabis* is characterised by prolonged vegetative development and relatively longer stems (Sengloung, Kaveeta and Nanakorn, 2009). Generative maturity can be delayed, and in extreme cases, plants are harvested with undeveloped flowers. In moderate climates, the optimal sowing date for hemp is late April or early May. *Cannabis* does not have specific soil requirements, but the soil pH should be close to neutral or slightly alkaline. If necessary, soil should be limed before sowing.

The yield and pharmaceutical quality of hemp plants are primarily determined by plant variety and agricultural treatments, particularly fertilisation and sowing density. Nitrogen is the key nutrient in hemp production. According to Farnisa *et al.* (2023) and Struik *et al.* (2000), nitrogen fertilisation influences plant habit, leaf surface area, chlorophyll content, physiological parameters, and the dry matter yield of stems. *Cannabis* plants have a particularly high demand for nitrogen in the early stages of vegetative development. Additionally, soil nitrogen levels are closely correlated with the THC content of *Cannabis* leaves and their position on the plant. Wee *et al.* (2025), Dilena *et al.* (2023), Navdeep *et al.* (2023) and Saloner and Bernstein (2022) demonstrated that the nitrogen content of vegetative plant parts was positively correlated with THC levels. Hemphill, Turner and Mahlberg (1980) found that the THC content of leaves decreased gradually from the top to the bottom of the plant. Dilena *et al.* (2023) observed that high soil nitrogen levels led to a greater reduction in the THC content of older than younger hemp leaves.

Silicon (Si) is another important factor that contributes to the performance of *Cannabis* plants. Silicon not only stimulates life processes but also protects plants against multiple abiotic and biotic stressors, increasing their resistance to various pathogens. Additionally, silicon promotes phosphorus uptake, increases photosynthetic efficiency, decreases the transpiration rate (protecting plants against excessive water loss), reduces susceptibility to lodging, and strengthens plant cell walls (Ma and Yamaji, 2006; Barão and Teixeira, 2015).

Sowing density depends on the intended use of the crop. In *Cannabis* plants grown for biomass, three target populations were established at densities of 30, 90, and 270 plants$\cdot$m^{-2} (Struik *et al.*, 2000). Campiglia, Radicetti and Mancinelli (2017) examined hemp stand densities of 40, 80, and 120 plants$\cdot$m^{-2}. *Cannabis sativa* is usually sown at high rates due to its competitiveness against weeds. Bennett, Snell and Wright (2006) sowed hemp at densities of 150–300 seeds$\cdot$m^{-2}, and Amaducci *et al.* (2008) at 120–360 seeds$\cdot$m^{-2}. For *Cannabis* grown for seeds, the seeding rate was 10–15 kg seeds$\cdot$ha^{-1} (Grabowska and Koziara, 2001).

The gradual recognition and introduction of legal regulations on hemp production and use in the European Union (Żuk-Gołaszewska and Gołaszewski, 2020) has increased the popularity of this plant species among farmers. In Poland, *C. sativa* cultivation is well-justified by the country's evolving climate conditions, existing agricultural expertise, and the crop's economic and environmental benefits. The extended growing seasons resulting from climate change create increasingly favourable conditions for hemp cultivation, addressing the query's question about whether the plant can prosper in Poland's climate (Poniatowska *et al.*, 2019). Polish-developed hemp varieties demonstrate excellent adaptation to local conditions, producing high yields of both fibre and seeds (Wawro *et al.*, 2021; Teleszko *et al.*, 2022). The legal framework, while complex and evolving, currently accommodates industrial hemp cultivation, though regulatory uncertainties remain a challenge for sector development. As Poland continues to experience climate change impacts on agriculture, hemp represents a promising alternative crop that can thrive in the changing conditions while providing economic opportunities for farmers and supporting environmental sustainability (Swora-Cwynar *et al.*, 2025). Further research into hemp cultivation practices specifically adapted to Polish conditions will help maximise the potential of this versatile crop in the country's agricultural landscape.

Given the above, the present study was undertaken to evaluate the growth, yield and physiological characteristics of *C. sativa* by analysing photosynthesis, transpiration, and some biophysical parameters of plants at different growth stages in response to varied soil conditions and agronomic factors (nitrogen fertilisation, silicon application, and sowing density) in an on-farm experiment.

MATERIALS AND METHODS

STUDY SITE AND EXPERIMENTAL DESIGN

The field experiment was established in 2020 on a farm in Linowiec, Poland (53°25'33" N, 19°44'37" E). It commenced in April by collecting the soil samples and ended in September, after the harvest and collection of the soil samples at the end. The studied cultivar was *Cannabis sativa* cv. Futura 75. This late-flowering, monoecious cultivar had been developed in France. Flowering begins in mid-August; plants reach a height of 2.5–4.0 m, and inflorescence yields approximate 3 t·ha^{-1} (Baldini *et al.*, 2018). Straw yields reach 20 t·ha^{-1} at a moisture content of 16%. Futura 75 has a thousand seed mass of 18.9 g with a germinating capacity of 80%. The seedbed was prepared by ploughing, followed by rotary cultivation. The soil in the experimental field was classified as a non-calcareous brown soil – Eutric Cambisol according to IUSS (2022), having sandy loam texture (40% sand, 37% silt, 23% clay; S1 – loamy soil) and loamy sand texture (48% sand, 34% silt, 18% clay; S2 – sandy soil).

The experiment employed a non-replicated full 2^4 factorial design, where four factors were tested at two levels each. There were no pseudo-replicates but single plots with 4-factor combinations. In the absence of replication, we followed standard practice by assuming that higher-order interactions (three- and four-factor) are negligible and used their mean squares as an estimate of experimental error. The single plot size was 18 m^2. The tested soils and agronomic factors were: type of soil (S1: loamy soil, S2: sandy soil), sowing density (D1: 6 kg·ha^{-1} and D2: 10 kg·ha^{-1}), nitrogen fertilisation rate (urea applied at N1: 0 and N2: 60 kg·ha^{-1}, 20 days after seedling emergence) and silicon application (Optysil biostimulant applied at Si1: 0 and Si2: 0.5 dm^3·ha^{-1}, 42 days after seedling emergence). Table 1 shows the distribution of experimental units.

Table 1. Layout of experimental units in the field experiment

Plot number	Type of soil	Silicon application	Sowing density	Nitrogen application
1	S1	Si2	D2	N1
2	S1	Si1	D1	N1
3	S1	Si1	D2	N1
4	S1	Si1	D1	N2
5	S1	Si2	D1	N2
6	S1	Si2	D2	N2
7	S1	Si2	D1	N1
8	S1	Si1	D2	N2
9	S2	Si2	D1	N1
10	S2	Si1	D2	N1
11	S2	Si1	D1	N2
12	S2	Si1	D1	N1
13	S2	Si1	D2	N2
14	S2	Si2	D2	N2
15	S2	Si2	D1	N2
16	S2	Si2	D2	N1

Explanations: S1 = loamy soil, S2 = sandy soil; Si1 = no silicone application, Si2 = 0.5 dm^3·ha^{-1} silicon application, D1 = sowing density 6 kg·ha^{-1}, D2 = sowing density 10 kg·ha^{-1}, nitrogen fertilisation rate: N1 = no fertilization, N2 = 60 kg N·ha^{-1}.
Source: own elaboration.

Soil properties

Soil samples were collected before sowing and after harvest according to Standard PN-R-04031:1997 (Polski Komitet Normalizacyjny, 1997), to determine the chemical properties of soil. The content of total organic carbon (TOC) and total nitrogen (TN) were determined with the Vario MaxCube CN elemental analyser. Soil pH was determined potentiometrically in water and 1 M KCl. For the sum of exchangeable alkaline cations (SBC; i.e. Ca^{2+}, Mg^{2+}, K^+, Na^+), the 10 g of air-dried soil sample was treated with 50 cm^3 of 0.1 M HCl (1:5 w:v). The solution was shaken for one hour at rotary shaker (40 rpm), at room temperature and then filtrated. The filtrate was titrated with 0.1 M NaOH in presence of phenolphthalein indicator. The SBC was calculated from the amount of sodium hydroxide solution used (Jaremko and Kalembasa, 2014). For the hydrolytic acidity (H^+ ions), the 20 g of air-dried soil sample was treated with 50 cm^3 of 1 M CH_3COONa (1:2.5 w/v). The solution was shaken for one hour at rotary shaker (40 rpm), at room temperature, and then filtrated. The filtrate was titrated with 0.1 M NaOH in presence of phenolphthalein indicator and the H^+ ions content was calculated from the amount of sodium hydroxide consumed (Jaremko and Kalembasa, 2014). The cation exchange capacity (CEC) was calculated as the sum of SBC and H^+ ions, and the base saturation (BS) was calculated as a share of SBC in CEC and expressed in percentage. The concentration of plant-available phosphorus was analysed using the Egner–Riehm method in 0.04 M $C_6H_{10}CaO_6$ (calcium lactate) + 0.02 M HCl at pH 3.7 (soil-solution ratio – 1:20, extraction time – 120 min) according to procedure (Komosa and Stafecka, 2003). For the content of potentially labile forms of Ca, Mg, K, Fe, Mn, 5 g of air-dried soil samples were treated with 50 cm^3 of 1 M HCl, shaken for one hour at rotary shaker (40 rpm), at room temperature, and then filtrated. The content of elements in the filtrate was measured at the iCAP Duo 7400 Thermo Scientific ICP-OES spectrometer.

Weather conditions

Meteorological data in successive phenological stages of *C. sativa* were expressed by three indicators: DAS – days after sowing until the achievement of a specific growth phase – seedling emergence, vegetative growth in the 6th, 8th and 9th true leaf pair, and flowering (flower formation beginning and full flowering); GDD – growing degree days in degrees Celsius as the accumulation of daily mean temperatures on the assumption that the base temperature must be exceeded by 1.4°C for growth to occur (Lisson, Mendham and Carberry, 2000); AP – accumulated precipitation in mm. The meteorological data were acquainted from the Meteorological Station of the University of Warmia and Mazury in Bałcyny (53°35'46.4" N, 19°51'19.5" E) located in the distance of 24 km from the farm. *Cannabis* plants grown on loamy and sandy soils achieved successive growth stages on similar dates. The growing season (from sowing to harvest) lasted 88 days and the weather conditions during the growing season were moderately favourable for the growth and development of *Cannabis* plants (Tab. S1). In successive months, mean daily temperature increased steadily from 10.1°C in May to 19.2°C in August. Precipitation was determined at 64.0 mm in May, 99.3 mm in June, 39.7 mm in July, and 107.2 mm in August. The 2nd leaf pair, when the first roots and leaves appear, lasted 20 DAS with GDD = 314°C and AP = 24.1 mm. The vegetative stage, when the 6th, 8th and 9th leaf pairs, lasted 14 DAS with GDD = 535.8°C and AP = 103.3 mm. The flowering stage with three ontogenetic phases lasted 14 DAS with GDD = 404.7°C and AP = 30.6 mm. During the entire growing season, GDD = 1283.2°C and AP = 158.1 mm.

Moreover, the Selianinov hydro-thermal coefficient (*HTC*) was calculated, as it is a climate index used to assess agricultural drought by comparing precipitation and temperature during the growing season (Evarte-Bundere and Evarts-Bunders, 2012). The *HTC* (Eq. (1)) is:

$$HTC = \frac{\sum P}{0.1 \sum T} \tag{1}$$

where: ΣP = total precipitation during the growing season (mm), ΣT = sum of daily average temperatures above 10°C during the same period.

Values <1 indicate dryness. In our study the total precipitation was 206.9 mm and the sum temperatures was 1606.6°C. Then, the *HTC* equals 1.29 which suggest wetter conditions.

PLANT ANALYSES

The *C. sativa* cv. Futura 75 seeds were sown on 29 May 2020, with a row spacing of 50 cm. The following parameters of plant growth and development were analysed during the growing season: physiological processes, including photosynthesis (*Pn*), transpiration (*E*) and water use efficiency (*WUR* = *Pn*/*E*), and biophysical parameters, including nitrogen status measured with a SPAD chlorophyll meter, and the leaf area index (*LAI*).

The physiological processes were measured during entire growing season with the LI-6400 Portable Photosynthesis System equipped with a 5 cm^2 leaf chamber (Żuk-Gołaszewska, 2008): SPAD – 5 measurements at seedling stage (Jun 17 and Jun 26), 1st leaflet (Jul 02), 2nd leaflet (Jul 09) and 3rd leaflet (Jul 16); photosynthesis and transpiration – 4 measurements at seedling stage (Jun 26), 1st leaflet (Jul 02), 2nd leaflet (Jul 09) and 3rd leaflet (Jul 16). Leaf temperature during the measurements ranged from 20 to 25°C. The *LAI* was determined with the LI-COR LAI-2200 Plant Canopy Analyzer (LI-COR Inc Biosciences, 2010). In turn, chlorophyll content was measured in the centre of the middle of leaflet with the SPAD-502 chlorophyll meter (Konica Minolta, Japan). SPAD values are dimensionless numerical values that are proportional to the total amount of chlorophyll in a leaf (Peltonen, Virtanen and Haggren, 1995).

The plants were harvested on 24 August 2020 in the flowering stage. Directly after harvest, inflorescences were dried under natural conditions in a farm building. According to the literature, inflorescences should be dried for 15 h at a temperature of 40°C immediately after harvest to obtain high-quality raw material (Upton *et al.*, 2013). Plant height, inflorescence length, and inflorescence dried mass were determined after harvest.

STATISTICAL ANALYSIS

Plant height is one of morphological traits that can provide a non-destructive insight into plant growth and development during growing season. For the sake of modelling plant height was measured in the seven stages of plant growth and development: DAS = 20, 35, 42, 49, 57, 64, and 71 days after sowing and the mean values from 16 plants per plot were the basis for modelling plant height development.

Plant height parameters were estimated with the use of the following non-linear function (Eq. (2)):

$$\omega_i = f(t_i, \mathbf{B}) + \varepsilon_i \tag{2}$$

where: i = 1, 2, …, n and n = number of observations; ω = plant height; t = the number of days after sowing (DAS); **B** = the vector of unknown parameters p, where $\beta_j = \beta_1, \beta_2, \ldots, \beta_p$; ε_i = a random error term.

The estimators of β_j are found by minimising the sum of squared residuals (Eq. (3)):

$$SS_{\mathrm{Res}} = \sum_{i=1}^{n} (\omega_i - f(t_i, \mathbf{B}))^2 \tag{3}$$

The four-parameter Weibull model estimated for soil types and agricultural treatments (sowing density, nitrogen fertilisation, and silicon application), had the following integral form (Eq. (4)):

$$\omega(t) = \beta_0 - \beta_1 e\left(-\beta_2 t^{\beta_3}\right) + \varepsilon \tag{4}$$

The resulting sigmoidal curve demonstrated that plant height increased slowly after emergence, then increased exponentially through the point of inflection with a maximum plant height growth rate and the time at which it occurred, then increased slowly to the curve plateaus. The iterative Levenberg-Marquardt (LM) method applied in parameter estimation requires initial values for each of the parameters. The following initial values of plant height were used in the model: β_0 is the maximum possible value of plant height; β_1 is the biological constant which is determined at the beginning of growth when t = 0; β_2 is the constant rate at which plant height approaches the maximum possible value β_0; and β_3 is the allometric constant with values >1 for sigmoidal function, otherwise it has no inflection point.

The plant height growth rate $\frac{d\omega}{dt}$, the relative plant height growth rate *RPHGR* as a function of plant height, the maximum plant height growth rate $PHGR_{\max}$, and the point of inflection $\omega(t)$ were estimated according to the following Equations (5)–(8):

$$\frac{d\omega}{dt} = \beta_1 \beta_2 \beta_3 t^{\beta_3 - 1} \, e^{-\beta_2 t^{\,\beta_3}} \tag{5}$$

$$RPHGR = \beta_1\beta_2\beta_3 t^{\beta_3 - 1}\left(\beta_0 e^{\beta_2 t^{\beta_3}} - \beta_1\right)^{-1} \quad (6)$$

$$PHGR_{\max} = \beta_1\beta_3\beta_2^{\frac{1}{\beta_3}} e^{\frac{1-\beta_3}{\beta_3^2}} \quad (7)$$

$$\omega(t) = \beta_0 - \beta_1 e^{\frac{1-\beta_3}{\beta_3}} \quad (8)$$

Plant height growth rate models were compared with the root mean-square error (*RMSE*):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\omega_i - \hat{\omega}_i)^2}{n-p}} \quad (9)$$

where: ω_i = actual value for the i^{th} observation; $\hat{\omega}_i$ = predicted value for the i^{th} observation; n = number of observations; p = number of parameter estimates.

Plant height growth rate, physiological and biophysical parameters measured during the growing season, and yield components measured after harvest were analysed by factorial ANOVA. The significance of differences between the main effects and the interaction effects was evaluated by Tukey's HSD test. Only main and significant interactions were presented in the paper while the rest of insignificant interactions were used to estimate the error term. The simple regression method was applied to evaluate the empirical relationship between the studied physiological parameters and yield components. The level of significance was set at $p < 0.01$ in analyses of soil properties and $p < 0.05$ in plant analyses.

Statistical analyses, including non-linear estimation, ANOVA, and simple regression, were performed using the Statistica (TIBCO Software Inc. (2017)) package.

RESULTS

SOIL CHEMICAL PROPERTIES OF EXPERIMENTAL PLOTS

Soil properties before the experiment

The experimental fields comprised loamy and sandy soils with different nutrient capacity and sorptive properties (Tab. 2). Soil pH measured in H_2O was 6.39 (slightly acidic) in loamy soil and 6.93 (neutral) in sandy soil. Loamy soil contained 0.24% of total nitrogen and 2.03% of total organic carbon. In sandy soil, the content of nitrogen was two-fold lower and carbon was three-fold lower (0.12 and 0.63%, respectively). The analysed soils had different sorption properties. Hydrolytic acidity, sum of exchangeable alkaline cations (SBC), and cation exchange capacity (CEC) were higher in loamy soil than in sandy soil. Base saturation differed in the examined soil types. The value of this parameter was lower in loamy soil than in sandy soil.

Change of soil properties after the experiment

Total nitrogen and organic carbon contents did not show noteworthy differences. The soil pH (measured in H_2O and in KCl) in loamy and sandy soils increased after harvest. Iron was the only nutrient whose content increased in both soil types by around 10% after *Cannabis sativa* cultivation. In loamy soil,

Table 2. Chemical properties of loamy and sandy soils before sowing and after harvest of *Cannabis sativa* L. (arithmetic mean ±standard deviation)

Soil parameter	Unit	Loamy soil		Sandy soil	
		before sowing	after harvest	before sowing	after harvest
pH(H_2O)		6.39 ±0.182	6.50 ±0.105	6.93 ±0.083	6.98 ±0.091
pH(KCl)		5.30 ±0.334	5.38 ±0.404	6.62 ±0.391	6.75 ±0.195
TN	%	0.24 ±0.036	0.25 ±0.031	0.12 ±0.006	0.12 ±0.012
TOC	%	2.03 ±0.39	2.08 ±0.355	0.63 ±0.057	0.61 ±0.075
C/N		8.42 ±0.43	8.39 ±0.484	5.6 ±0.553	5.44 ±0.177
P_2O_5	$mg\cdot(100\ g)^{-1}$	7.07 ±2.32	3.14 ±0.74	14.6 ±1.77	7.7 ±1.95
Ca	$g\cdot kg^{-1}$	2.25 ±0.608	2.3 ±0.798	2.18 ±0.995	1.98 ±0.482
Mg	$g\cdot kg^{-1}$	0.17 ±0.045	0.14 ±0.035	0.25 ±0.36	0.11 ±0.024
Na	$g\cdot kg^{-1}$	0.03 ±0.016	0.02 ±0.011	0.02 ±0.007	0.01 ±0.003
K	$g\cdot kg^{-1}$	0.25 ±0.023	0.22 ±0.013	0.17 ±0.015	0.15 ±0.017
Fe	$g\cdot kg^{-1}$	1.71 ±0.159	1.89 ±0.203	0.63 ±0.051	0.7 ±0.097
Mn	$mg\cdot kg^{-1}$	148.7 ±5.69	157.7 ±12.6	113.7 ±11.0	111.6 ±7.68
H+	$mmol\ (+)\cdot(100\ g)^{-1}$	3.10 ±1.60	1.67 ±1.21	1.77 ±1.24	2.69 ±1.16
SBC	$mmol\ (+)\cdot(100\ g)^{-1}$	11.5 ±2.51	12.3 ±3.07	7.98 ±2.26	10.2 ±2.13
CEC	$mmol\ (+)\cdot(100\ g)^{-1}$	14.6 ±2.81	14.0 ±3.83	9.74 ±3.37	12.9 ±1.81
BS	%	78.9 ±10.4	88.6 ±5.99	83.6 ±6.65	78.9 ±9.35

Explanations: TN = total nitrogen, TOC = total organic carbon, SBC = sum of exchangeable alkaline cations, CEC = cation exchange capacity, BS = base saturation.
Source: own study.

a minor increase was also noted in the content of calcium (2.1%) and manganese (6.0%). After harvest, the content of P, K, Na, and Mn decreased, whereas Ca content increased slightly (by 2.1%) in loamy soil and decreased by 9.0% in sandy soil. *Cannabis* plants took up large quantities of phosphorus in both soil types (P_2O_5 content decreased by 55.6% in loamy soil and by 47.1% in sandy soil). In comparison with loamy soil, sandy soil was characterised by a significant decrease in magnesium levels (59.4%) and a significant increase in sorption properties, including hydrolytic acidity – H^+ (52.1%), SBC (28.2%), and CEC (32.5%). The percent changes in soil properties during the growing season of *C. sativa* and significant soil type × sampling date interactions for phosphorus content, hydrolytic acidity, and base saturation are presented in Figure 1. The direction of phosphorus uptake by plants was identical in both soil types, but *C. sativa* took up more phosphorus in loamy soil than in sandy soil. The transition of hydrolytic acidity and base saturation proceeded in opposite directions in the analysed soils. In loamy soil, the decrease in hydrolytic acidity was associated with an increase in base saturation, whereas in sandy soil, hydrolytic acidity increased with a concurrent decrease in base saturation. It is worth noting that *C. sativa* generally took up large amounts of magnesium and sodium whose content decreased by 42 and 14.6%, respectively. However, these differences were not statistically significant.

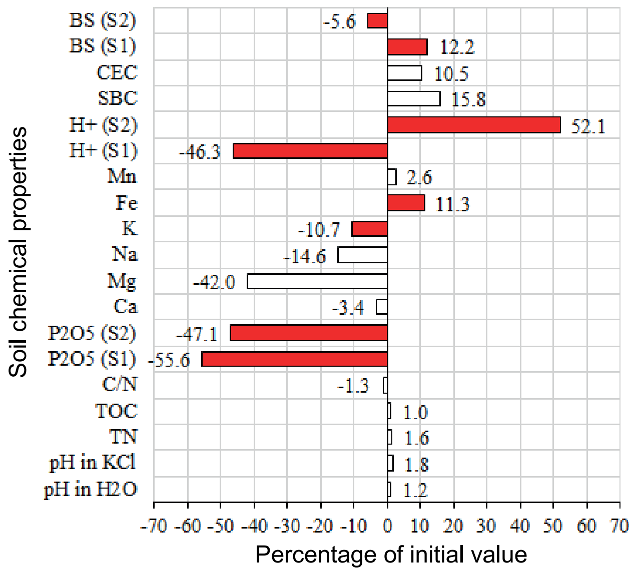

Fig. 1. Percentage change of soil parameters during growing season ((mean value after harvest/mean value before sowing)·100); S1 = loamy soil, S2 = sandy soil, BS, CEC, SBC, TOC, TN as in Tab. 2; red bars indicate statistical significance; source: own study

PLANT HEIGHT GROWTH RATE MODELS

In all plant height growth rate models, the estimated parameters β_0, β_1, and β_3, as well as parameter β_2 for sandy soil (S2), silicon application (Si2), lower sowing density (D1), and no nitrogen fertilisation (N1) were statistically significant (Tab. 3). Consequently, it can be assumed that all models provided good estimates of plant height and the plant height growth rate during the entire growing season.

The highest maximum height growth rate (14.8 cm) and point of inflection (144.6 cm) were determined on loamy soil, whereas the lowest values of these parameters were noted on sandy soil (8.2 cm and 72.1 cm, respectively). In other agricultural treatments, relatively higher values were estimated for silicon application, and lower values were noted for sowing density and no nitrogen fertilisation. The predicted values of plant height and the plant height growth rate are presented in Figure 2.

Soil type, followed by silicon application were characterised by greatest differences in distribution parameters. However, the plant height growth rate was nearly twice higher on loamy soil (S1) due to greater variation in the results than on sandy soil, whereas the variation associated with silicon application was smaller in treatments without silicon application. In treatments with lower sowing density (D1) and no nitrogen application (N1), plant height and the plant height growth rate were slightly higher than in the remaining treatments. A significant difference in the relative plant height growth rate was associated only with soil type, where a high rate was noted on loamy soil (S1). The final growth stage proceeded much more slowly on sandy soil with silicon application (<0.1 cm·d^{-1}) than in other treatments.

Table 3. Estimated Weibull distribution parameters (β_0, β_1, β_2, β_3), maximum plant height growth rate ($PHGR_{max}$), point of inflection ($\omega(t)$) and root mean square error ($RMSE$) for plant height growth rate under different agricultural conditions

Agricultural factors	Treatments	β_0	β_1	β_2	β_3	$PHGR_{max}$ (cm)	$\omega(t)$ (cm)	*RMSE*
Soil type	loamy soil	350**	354**	1.19E-05	2.84**	14.8	144.6	13.8
	sandy soil	144**	143**	5.06E-06**	3.21**	8.24	72.1	1.4
Silicone application	no silicone	246**	249**	4.15E-05	2.53*	9.2	109.9	11.0
	silicone application	242**	242**	1.64E-06**	3.44**	14.0	123.0	5.9
Sowing density	6 kg per ha	239**	239**	3.53E-06**	3.21**	12.5	118.6	6.3
	10 kg per ha	240**	242**	2.12E-05	2.75*	10.5	111.4	11.1
Nitrogen fertilization	no nitrogen fertilization	247**	246**	2.95E-06**	3.25**	12.8	123.3	4.3
	nitrogen fertilization	230**	233**	2.20E-05	2.75*	10.3	106.6	12.5

Explanations: *, ** = significant at $p < 0.05$ and $p < 0.01$, respectively; β_0 = maximum possible value of plant height; β_1 = biological constant which is determined at the beginning of growth when $t = 0$; β_2 = the constant rate at which plant height approaches the maximum possible value β_0; and β_3 = the allometric constant with values >1 for sigmoidal function, otherwise it has no inflection point.
Source: own study.

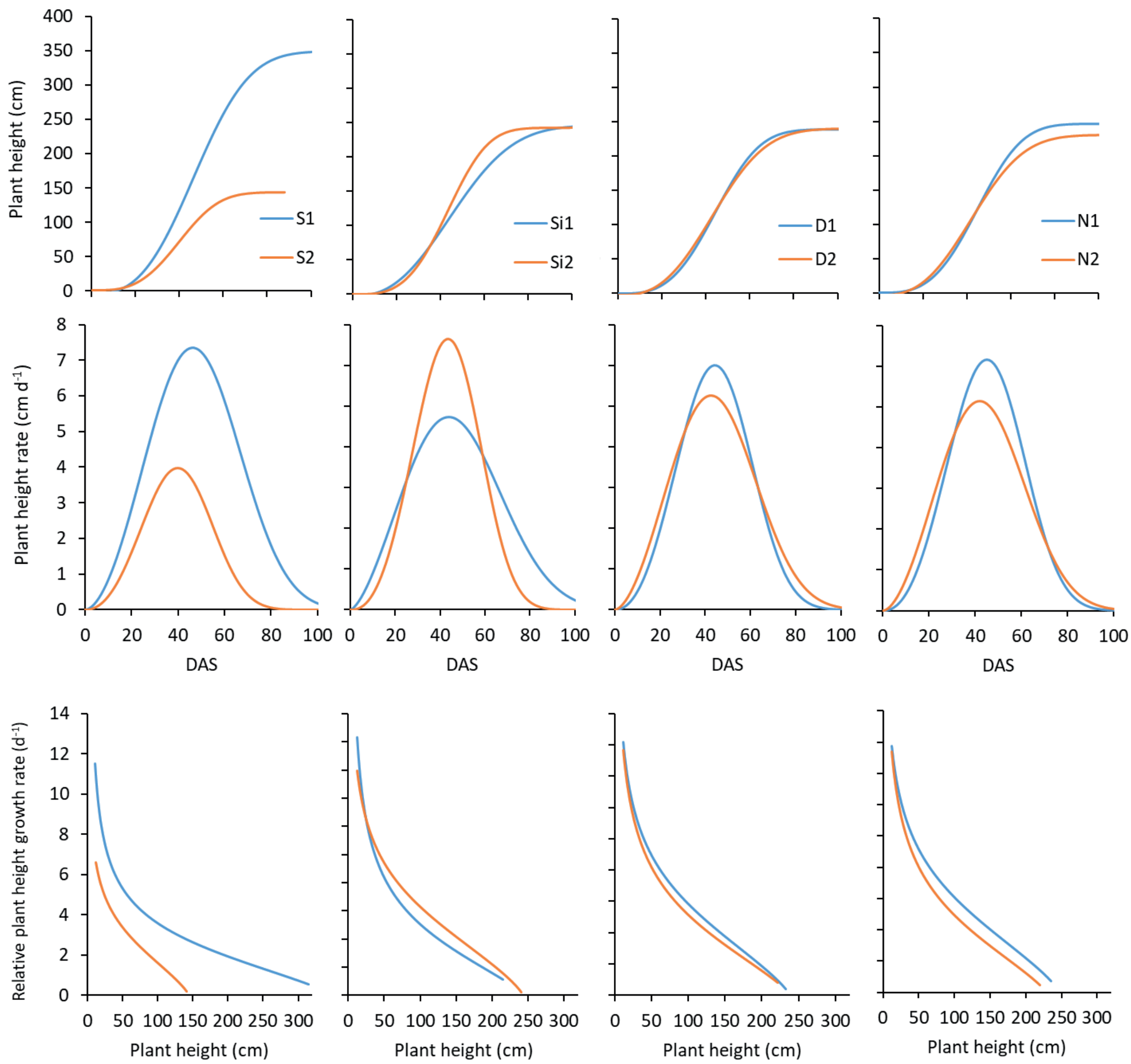

Fig. 2. Weibull model prediction of plant height, plant height rate, and relative plant height growth rate in different agricultural conditions; S1 = loamy soil, S2 = sandy soil; Si1 = no silicone application, Si2 = 0.5 $dm^3 \cdot ha^{-1}$ silicone application; D1 = sowing density 6 $kg \cdot ha^{-1}$, D2 = sowing density 10 $kg \cdot ha^{-1}$; N1 = no fertilization, N2 = 60 kg $N \cdot ha^{-1}$ at the stage of one leaflet, DAS = days after sowing; source: own study

PLANT PHYSIOLOGICAL AND BIOPHYSICAL TRAITS

The main effects of photosynthesis-related processes differed significantly across soil types and nitrogen fertilisation treatments (Tab. 4). The rates of photosynthesis and transpiration were significantly higher on loamy soil than on sandy soil. As could be expected, on average during the growing season, water use efficiency as the reverse transpiration effect was significantly lower (by 26%) on loamy soil. Nitrogen fertilisation (N2) was the only agricultural treatment that increased transpiration (by 13%).

During the growing season, the instantaneous net photosynthesis rate ranged from 25.2 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ at 28 DAS on sandy soil to 40.4 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ at 49 DAS on loamy soil. The only significant nitrogen fertilisation × DAS interaction resulted from a significant difference between the effects of nitrogen treatments at 28 DAS, 31.6 and 26.9 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, without and with nitrogen fertilisation, respectively. In successive stages of vegetative growth, only a minor increase in the instantaneous net photosynthesis rate was observed in response to nitrogen fertilisation.

The transpiration rate and water use efficiency differed considerably across growth stages. For both traits, a significant soil type × DAS interaction was related to the reciprocal effect, depending on soil type. On loamy soil, the transpiration rate was significantly higher in initial growth stages, which decreased water use efficiency, but the values of both parameters were similar in successive stages. The above implies that in subsequent growth stages of *C. sativa*, increased transpiration was associated with a relatively higher rate of photosynthesis. On sandy soil, transpiration initially decreased and then steadily increased, whereas water use efficiency initially increased and decreased in later stages.

Significant differences in the leaf greenness index (SPAD) were observed between soil types and nitrogen treatments. Excluding the first measurements conducted at 20 DAS, SPAD values were higher on loamy soil than on sandy soil. A gradual increase in SPAD values was noted during the entire growing season, and this parameter peaked at 49 DAS on loamy soil. At 49 DAS, SPAD was also higher in treatments with than without nitrogen fertilisation. In the remaining treatments (with silicon application and higher sowing density), only a minor increase in

Table 4. Mean values of the interaction effects between agricultural treatments and growth stages (DAS)

DAS (growth stage)	Soil type		Silicon application		Sowing density		Nitrogen fertilization	
	S1	S2	Si1	Si2	D1	D2	N1	N2
Instantaneously net photosynthesis rate (*Pn*, µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)								
28 (4th leaf pair)	33.3	25.2	28.5	30.0	27.1	31.4	31.6_{bA}	26.9_{bB}
35 (6th leaf pair)	31.3	23.3	26.1	28.5	27.0	27.6	26.6_{cA}	27.9_{bA}
42 (8th leaf pair)	31.3	27.4	28.8	29.8	28.3	30.4	27.8_{cA}	30.8_{bA}
49 (9th leaf pair)	40.0	34.2	36.5	37.7	37.6	36.6	36.9_{aA}	37.2_{aA}
Transpiration rate (*E*, µmol $H_2O \cdot m^{-2} \cdot s^{-1}$)								
28 (4th leaf pair)	0.57_{cdA}	0.79_{bA}	0.58	0.78	0.78	0.58	0.63	0.73
35 (6th leaf pair)	2.02_{aA}	0.34_{cB}	1.23	1.14	1.25	1.11	1.10	1.26
42 (8th leaf pair)	1.84_{abA}	0.93_{bB}	1.35	1.42	1.29	1.48	1.16	1.61
49 (9 h leaf pair)	1.54_{bA}	1.47_{aA}	1.36	1.66	1.58	1.43	1.51	1.51
Instantaneous water use efficiency (*WUE* = *Pn*/*E*)								
28 (4th leaf pair)	91.7_{aA}	46.2_{bB}	77.9	60.0	60.6	77.3	81.4	56.5
35 (6th leaf pair)	18.7_{bB}	95.1_{aA}	67.4	46.4	52.8	61.0	55.8	58.0
42 (8th leaf pair)	21.1_{bA}	43.2_{bA}	31.9	32.3	32.1	32.1	41.5	22.8
49 (9th leaf pair)	28.1_{bA}	27.1_{bA}	30.9	24.3	27.8	27.5	27.1	28.1
Leaf greenness index (SPAD)								
20 (2nd leaf pair	37.5_{cA}	37.6_{bcA}	37.4	37.6	38.2	36.9	38.1_{cA}	37.0_{cA}
28 (4th leaf pair)	41.5_{bcA}	36.6_{bcB}	38.6	39.5	38.9	39.3	39.0_{bA}	39.2_{bA}
35 (6th leaf pair)	42.4_{bcA}	35.2_{cB}	38.2	39.3	38.4	39.1	38.8_{bA}	38.7_{bA}
42 (8th leaf pair)	45.1_{bA}	38.9_{bcB}	41.7	42.4	42.1	41.9	39.9_{abB}	44.2_{bA}
49 (9th leaf pair)	51.3_{aA}	44.5_{aB}	47.5	48.2	48.3	47.5	44.6_{aB}	51.1_{aA}
Leaf area index (*LAI*, $m^2 \cdot m^{-2}$)								
28 (4th leaf pair)	2.75_{cA}	2.54_{aA}	2.61_{abA}	2.68_{cA}	2.54	2.74	2.36	2.92
35 (6th leaf pair)	3.32_{bA}	2.09_{bB}	2.52_{bB}	2.89_{bcA}	2.50	2.91	2.35	3.06
42 (8th leaf pair)	3.97_{aA}	2.67_{aB}	3.04_{aB}	3.60_{aA}	3.22	3.42	3.05	3.58

Explanations: Tukey's HSD test: lowercase letters denote differences between columns, and block letters denote differences between rows; DAS = days after sowing, S1, S2, Si1, Si2, D1, D2, N1, N2 as in Fig. 2.
Source: own study.

SPAD values was noted across growth stages. The difference in SPAD between the first and last measurement was around 20%.

The leaf area index was significantly influenced by all of the analysed agricultural treatments. This parameter was higher on loamy soil than on sandy soil (3.34 vs. 2.43 $m^2 \cdot m^{-2}$), in treatments with silicon application than in treatments without silicon application (3.05 vs. 2.72 $m^2 \cdot m^{-2}$), in treatments with increased sowing density (3.02 vs. 2.75 $m^2 \cdot m^{-2}$ at initial density), and in treatments with nitrogen fertilisation than in treatments without nitrogen fertilisation (3.19 vs. 2.59 $m^2 \cdot m^{-2}$). Two significant soil type × DAS and silicon treatment × DAS interactions were observed. The leaf area index increased significantly on loamy soil and in treatments with silicon application during the entire growing season. On sandy soil and in treatments without silicon application, leaf area index (*LAI*) values were significantly higher only in the last measurements, relative to previous measurements.

The agronomic treatments did not influenced photosynthetic processes in the soils but impacted biophysical parameters – leaf greenness index (SPAD) and *LAI* (Tab. 5). The significant interaction type of soil × silicone application for SPAD resulted from a higher difference (15%) between loamy soil and sandy soil on treatments without silicone application than in treatments with silicone application (10%). Concurrently, nitrogen fertilisation did not impact SPAD on loamy soil but significantly increased SPAD on sandy soil. The effect of silicone application and sowing density on *LAI* on loamy soil was the same as in treatments with silicone application and a higher sowing density. Nitrogen fertilisation increased leaf area index on both types of soil, however the effect was higher on sandy soil (40%) than on loamy soil (25%).

YIELD COMPONENTS AT HARVEST

Yield components, including plant height, inflorescence length, and inflorescence dried mass, were strongly affected by soil type, fertilisation and sowing density (Tab. S2). Soil type was the main

Table 5. Interaction effects between type of soil and agronomic treatment for physiological indicators of plant growth and development; significant interaction was indicated by letters at means

Type of soil	Agronomic treatment	*Pn* (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)	*E* (μmol $H_2O \cdot m^{-2} \cdot s^{-1}$)	*WUE* (*Pn*/*E*)	SPAD	*LAI* ($m^2 \cdot m^{-2}$)
Loamy soil	no silicone	33.8	1.52	54.3	43.7a	3.39a
	silicone application	34.1	1.57	32.9	43.4a	3.29a
Sandy soil	no silicone	26.1	0.87	59.8	37.7b	2.05c
	silicone application	28.9	1.03	50.2	39.4b	2.82b
Loamy soil	lower sowing density	32.6	1.61	43.0	43.4	3.12a
	higher sowing density	35.3	1.48	44.2	43.7	3.57a
Sandy soil	lower sowing density	27.3	1.01	50.7	38.9	2.39b
	higher sowing density	27.7	0.88	59.3	38.2	2.48b
Loamy soil	no nitrogen	34.3	1.45	55.7	43.8a	3.15b
	nitrogen application	33.6	1.64	31.5	43.3a	3.54a
Sandy soil	no nitrogen	27.2	0.90	52.1	36.4c	2.03d
	nitrogen application	27.8	1.00	57.9	40.7b	2.84c

Explanations: Tukey's HSD test: lowercase letters denote differences between columns; *Pn*, *E*, *WUE*, SPAD, *LAI* as in Tab. 4.
Source: own study.

diversifying factor, and the values of yield components were more than twice higher on loamy soil than on sandy soil. On average, silicon application and lower plant density resulted in increased plant height, but it did not induce significant differences in the remaining yield components. In addition, a significant increase in inflorescence dried mass was noted in treatments with lower sowing density and no nitrogen fertilisation. It should be noted that a significant soil type × silicon application interaction for plant height and inflorescence dried mass resulted from non-significant differences in loamy soil and significant differences in sandy soil (93.0 vs. 175.0 cm and 0.93 vs. 2.88 g, respectively). A significant soil type × silicon application × sowing density interaction for all traits resulted from a significant increase in interaction effects on sandy soil with silicon application, whereas higher sowing density influenced only inflorescence dried mass.

The obtained results suggest that on loamy soil, *C. sativa* effectively utilised the natural potential of soil and that agricultural practices only slightly modified yield components.

The regression coefficients between yield components and physiological traits are presented in Table 6. The greenness index (SPAD), instantaneous net photosynthesis rate (*Pn*), and the leaf area index (*LAI*) significantly influenced yield components. Plant height increased by 28.1 cm, inflorescence length increased by 5.46 cm, and inflorescence dried mass increased by 0.311 g as SPAD value increased by one unit. Similarly, an increase in the instantaneous net photosynthesis rate by 1 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ increased plant height by 27.0 cm, inflorescence length by 4.81 cm, and inflorescence dried mass by 0.275 g. The leaf area index induced much greater changes in the examined parameters. Plant height increased by 111.0 cm, inflorescence length increased by 21.3 cm, and inflorescence dried mass increased by 1.402 g as *LAI* increased by one unit. Additionally, a significant regression was observed between transpiration rate and plant height (b = 164.1 cm per 1 μmol $H_2O \cdot m^{-2} \cdot s^{-1}$). Water use efficiency (indirect measure) was not significantly correlated with yield components.

Table 6. Regression coefficients between yield components and the physiological traits of *Cannabis sativa* L. (n = 16)

Physiological traits	Yield components								
	plant height			inflorescence length			inflorescence dried mass		
	$\widehat{b}$	p-value	R^2	$\widehat{b}$	p-value	R^2	$\widehat{b}$	p-value	R^2
SPAD	28.1	0.001	0.553	5.46	0.003	0.490	0.311	0.016	0.347
Pn	27.0	0.000	0.696	4.81	0.002	0.518	0.275	0.013	0.368
E	164.1	0.012	0.373	19.49	0.182	0.124	0.692	0.494	0.034
WUE	–2.4	0.159	0.136	–0.21	0.573	0.023	0.003	0.917	0.001
LAI	111.0	0.006	0.428	21.3	0.012	0.370	1.402	0.016	0.349

Explanations: $\widehat{b}$ = regression coefficient, R^2 = coefficient of determination; SPAD, *Pn*, *E*, *WUE*, *LAI* as in Tab. 4.
Source: own study.

DISCUSSION

KEY FINDINGS AND IMPLICATIONS

In the analysed growing season, weather conditions were moderately favourable for the growth and development of *Cannabis sativa*. The year 2020 was relatively cool with low precipitation levels, particularly during sowing and flowering. The mean daily temperature during the growing season was approximately 16°C, whereas the optimal temperature for effective photosynthesis in *Cannabis* plants is 25–35°C (Chandra *et al.*, 2011). Average precipitation during the growing season was 158.1 mm, while optimal precipitation for *C. sativa* ranges from 200 to 300 mm (Grabowska and Koziara, 2001), indicating that *C. sativa* plants were exposed to a mild water deficit during the season. *Cannabis* plants have an extensive root system and are tolerant to periodic dry spells, which are increasingly common in temperate climates (Gill *et al.*, 2022; Gill *et al.*, 2023). *Cannabis* grows well on soils with a loose texture and high clay content (Kostuik and Williams, 2019). The experimental soils met these requirements.

Nitrogen fertilisation and silicon application influence plant growth and soil conditions. Although silicon is the second most common element in the Earth's crust, not all silicon in the soil is available to plants. Most silicon occurs in recalcitrant silicate minerals, and only a small portion is available to plants (Struyf *et al.*, 2010). In this study, combined fertilisation with Si and N had a beneficial effect by improving the sorptive properties of soil, especially the content of base cations and cation exchange capacity in sandy soil, corroborating the findings of other researchers (Xu *et al.*, 2020). N and Si fertilisation did not significantly affect soil pH or carbon and nitrogen content, with similar results reported in other studies (Xu *et al.*, 2020). However, differences were observed between loamy and sandy soils. The content of total organic carbon (TOC) and total nitrogen (TN) increased in loamy soil, similar to observations made by other researchers analysing the influence of Si fertilisation on soil C content (Song *et al.*, 2012; Song *et al.*, 2014; Reithmaier *et al.*, 2017). Changes in OC, TN, and silicon content may influence soil fertility by improving water availability, chemical soil properties, and nutrient availability (Meena *et al.*, 2014; Greger, Landberg and Vaculík, 2018). Silicon fertilisers are produced from silicate minerals containing macro- and micronutrients such as K, Ca, Mg, and Fe (Kannan and Raj, 1998). The N or P content in the analysed soils could also have been affected by Si availability (Schaller *et al.*, 2012; Neu, Schaller and Dudel, 2017; Xu *et al.*, 2020). The content of Ca, Mg, Na, K, Fe, and Mn in soil changed after harvest (as compared to the content before sowing), but the observed differences were not significant (decrease or increase of 12%). However, the content of plant-available phosphorus decreased by 50%, suggesting that P may have been taken up by plants. Contrary to previous findings, Si fertilisation did not increase soil P content (Chinnasami and Chandrasekaran, 1978). Agricultural practices only slightly modified yield components in loamy soil, which suggests that *Cannabis* can grow well on either fertilised or non-fertilised loamy soils. However, application of fertilisers have to be carefully selected and managed on sandy soils. This study demonstrated that silicon application can significantly improve yield components on lighter soils at lower inputs associated with seeds and nitrogen fertilisers.

In the described experiment, the vegetative phase (from emergence to late flowering) of cv. Futura 75 lasted 71 days. In other studies, the vegetative phase of *C. sativa* lasted 81 days, however, in the southern Europe conditions (Campiglia, Radicetti and Mancinelli, 2017). *Cannabis* plants growing in less dense stands were somewhat taller, similar to results reported by Amaducci, Errani and Venturi (2002). In the present study, plant height was reduced in denser stands, which is not desirable when hemp is grown for fibre. Plant growth was inhibited at the beginning of flowering, similar to observations by Höppner and Menge-Hartmann (1995).

The instantaneous net photosynthesis rate ranged from 25 to 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$, influenced mainly by nitrogen fertilisation. A high photosynthetic rate in treatments with low nitrogen content (N1) confirms previous observations that *C. sativa* is a high-performing plant species (Struik *et al.*, 2000; Finnan and Burke, 2013). The transpiration rate was determined by soil quality. On average, plants grown on light soil were characterised by significantly lower transpiration rates and significantly higher water use efficiency than plants grown on heavy soil (0.94 vs 1.54 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 55.0 vs 43.6, respectively). In the results reported by Tang *et al.* (2017), the photosynthetic rate increased with a rise in leaf nitrogen content and was determined at 31.2 ±1.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at leaf temperature of 25°C. In a study by Saloner and Bernstein (2020), N increased the photosynthetic rate, the transpiration rate, and water use efficiency in hemp plants.

The non-invasive measurement of chlorophyll content (SPAD) is a well-known and practical method for quickly assessing the nitrogen status of plants. In this study, the nitrogen status of hemp, expressed in SPAD units, was influenced by soil quality and nitrogen fertilisation. SPAD values were generally higher in plants grown on loamy soil than on sandy soil. Conversely, sowing density and silicon (Si) application had no significant effect on SPAD values. Previous studies by Farnisa *et al.* (2023) and Anderson *et al.* (2021) also found that SPAD values in hemp (ranging from 44–56 SPAD) were influenced by the nitrogen rate and cultivar.

Soil type and fertilisation rates significantly affected leaf area index (*LAI*) values. Plants grown on loamy soil and supplied with Si and nitrogen exhibited higher *LAI* values. Similar results were reported by Zielonka *et al.* (2017), who found higher *LAI* values in hemp plants fertilised with sludge from a wastewater treatment plant and phosphogypsum.

Nitrogen fertilisation had no significant effect on plant height before harvest, inflorescence length, or inflorescence dried mass. In contrast, Atoloye *et al.* (2022) reported that bud biomass increased with higher nitrogen rates. Silicon application increased both inflorescence length and dried mass. However, these parameters were mainly determined by soil quality, with inflorescence length and dried mass being nearly twice as high in treatments on nutrient-rich heavy soil compared to light soil. The above lead to some outcomes for agronomists on *C. sativa* production. *Cannabis sativa* grown on loamy soil exhibited significantly greater growth and yield compared to sandy soil. Better physiological status and resource use were observed in loamy soils. These findings are consistent with other studies showing that nutrient-rich, heavier soils enhance hemp growth and yield (Poniatowska *et al.*, 2024). While loamy soils initially supported robust growth without fertiliser application, sustained production would require nutrient replenishment in subsequent growing cycles. Lower sowing density resulted in slightly taller plants, while higher sowing density increased *LAI* and, in some cases, inflorescence dried mass. However, the effect of sowing density on yield components was less pronounced than that of soil type. Notably, higher plant density can increase total yield per area despite reducing individual plant size, as reported in previous studies (Papastylianou, Kakabouki and Travlos, 2018; Poniatowska *et al*., 2022). Nitrogen fertilisation increased photosynthetic rate, SPAD (leaf greenness), and *LAI*, especially on sandy soil. However, its impact on final yield components (plant height, inflorescence length, dried mass) was minor compared to soil type. Silicon application improved yield components on sandy soil by enhancing soil cation exchange capacity and nutrient availability, but had limited effect on loamy soil. Nitrogen significantly boosted photosynthetic activity and chlorophyll content (SPAD), particularly at early growth stages. Silicon application increased *LAI* and improved plant physiological resilience, especially under less favourable soil conditions. These results align with broader research showing that nitrogen is critical for hemp biomass and inflorescence yield, and that silicon can mitigate abiotic stress and improve nutrient uptake (Poniatowska *et al*., 2019).

LIMITATIONS AND FUTURE WORK

One-year studies on *Cannabis sativa* cultivation, such as the described field experiment in Poland, provide valuable insights but face inherent limitations. These constraints stem from the short duration, environmental variability, and narrow scope of single-season investigations.

- Single-year data cannot account for interannual fluctuations in weather (e.g., temperature, precipitation) or extreme events (droughts, heatwaves), which significantly impact crop performance. For example, in the paper the 2020 study recorded moderate temperatures (16°C average) and low precipitation (158 mm), but results might differ under more extreme conditions.
- Long-term soil health changes (e.g., organic carbon depletion, nutrient cycling) and cumulative effects of agronomic treatments (e.g., silicon or nitrogen fertilisation) remain unaddressed. For example, the study noted a 50% reduction in soil phosphorus content after one season but did not evaluate multi-year trends.
- The experiment focused on a single cultivar (*Futura 75*), limiting insights into genetic diversity or cultivar-specific responses to stressors, including Polish-bred cultivars.
- Short-term studies lack cost-benefit analyses of agronomic practices (e.g., silicon application) or comparisons with rotational crops.
- Metrics like photosynthetic efficiency, water use, and not evaluated in the paper cannabinoid profiles may vary across plant developmental stages or under prolonged stress, which a single growing season cannot fully capture.

Taking into account those limitations future research on *C. sativa* should focus on multi-year trials to assess yield stability, soil health, and climate resilience; genotype-environment interactions under varying climatic zones and soil types to identify robust genotypes; climate change modelling to predict habitat suitability under future climate scenarios, particularly for regions facing temperature increases or water scarcity; and to quantify the profitability of hemp production relative to traditional crops and analyse regulatory barriers.

The presented results of pilot study advances scientific understanding of *C. sativa* agronomy by rigorously quantifying how soil type and management practices affect plant growth, physiology, and yield. It provides actionable insights for optimising hemp cultivation in temperate climates and offers a methodological template for future research in sustainable crop production.

CONCLUSIONS

This paper provides conclusions which are indicative for further research and the practice of agronomy that *Cannabis sativa* can be successfully cultivated on both loamy and sandy soils, but agronomic interventions (like silicon and nitrogen fertilisation) are particularly beneficial for sandy soils. Secondly, hemp is a competitive, low-input crop that can contribute to sustainable agriculture by reducing weed biomass without herbicides and by thriving under moderate fertiliser regimes. The present study provides new insights into the cultivation of *C. sativa* L. in the field. The study demonstrated that *C. sativa* grows well on soils with a high content of clay and silt fractions, i.e. loamy soils. In treatments established on loamy soil, the maximum plant height growth rate was 43% higher and plants were more than twice higher than on sandy soil (354 cm vs. 137 cm). The photosynthetic rate in successive stages of growth was similar on both soil types, but higher values of water use efficiency (*WUE*), leaf greenness index (SPAD), and leaf area index (*LAI*) were noted on loamy soil. The analysed agronomic factors modified plant growth and development to a relatively low extent. The photosynthetic rate and SPAD values were differentiated by nitrogen fertilisation, whereas *LAI* values were affected by silicon application. The values of SPAD and *LAI* were higher in *Cannabis* plants grown on sandy soil.

Combined fertilisation with silicon (Si) and nitrogen (N) exerted beneficial effects on soil, especially sandy soil, by improving soil cation exchange capacity and increasing the sum of base cations. This observation suggests that the yields of *Cannabis sativa* L. can be improved by increasing sowing density above 200 germinating seeds per square meter and either refraining from nitrogen fertilisation or applying N fertiliser at a rate of 60 kg per hectare in combination with silicon. Despite these treatments improved the properties of sandy soil, all yield components were significantly lower on sandy soil than on loamy soil, directly affecting the profitability of *C. sativa* production. The data indicate that *C. sativa* can be successfully cultivated on both loamy and sandy soils. However, agronomic interventions, such as the application of silicon and nitrogen, proved particularly beneficial on sandy soils. Notably, *C. sativa* exhibited strong competitiveness against weeds, eliminating the need for herbicide application. These findings support the characterisation of *C. sativa* as a low- to moderate-input crop, aligning with expectations and highlighting its potential contribution to sustainable and alternative agricultural systems. It is recommended to repeat the present study at a larger scale over a longer term to assess the economic, environmental effects, and aftereffects on crop rotation of *C. sativa* cultivation.

ABBREVIATIONS

AP = accumulated precipitation in mm
BS = base saturation
CBD = cannabidiol
CEC = cation exchange capacity
DAS = days after sowing until the achievement of a specific growth phase
E = transpiration
GDD = growing degree days in °C
HTC = hydro-thermal coefficient
LAI = leaf area index
$PHGR_{max}$ = maximum plant height growth rate
Pn = instantaneous net photosynthesis rate
RMSE = root mean square error
SBC = sum of exchangeable alkaline cations
SPAD = soil plant analysis development
THC = tetrahydrocannabinol
TN = total nitrogen
TOC = total organic carbon
WUE = water use efficiency

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_67_Zuk.pdf.

FUNDING

The research was supported by project No. 30.610.013-110, and No. 30.610.005-110 of the University of Warmia and Mazury in Olsztyn.

CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

REFERENCES

Amaducci, S., Errani, M. and Venturi, G. (2002) "Plant population effects on fibre hemp morphology and production," *Journal of Industrial Hemp*, 7, pp. 30–33. Available at: https://doi.org/10.1300/J237v07n02_04.

Amaducci, S. *et al.* (2008) "Influence of agronomic factors on yield and quality of hemp (*Cannabis sativa* L.) fibre and implication for an innovative production system," *Field Crops Research*, 107, pp. 161–169. Available at: https://doi.org/10.1016/j.fcr.2008.02.002.

Anderson, S.L. *et al.* (2021) "Response of essential oil hemp (*Cannabis sativa* L.) growth, biomass, and cannabinoid profiles to varying fertigation rates," *PLoS ONE*, 16, e0252985. Available at: https://doi.org/10.1371/journal.pone.0252985.

Atoloye, I.A. *et al.* (2022) "Hemp biochar impacts on selected biological soil health indicators across different soil types and moisture cycles," *PLoS ONE*, 17, e0264620. Available at: https://doi.org/10.1371/journal.pone.0264620.

Baldini, F. *et al.* (2018) "The performance and potentiality of monoecious hemp (*Cannabis sativa* L.) cultivars as a multipurpose crop," *Agronomy*, 8, pp. 162–178. Available at: https://doi.org/10.3390/agronomy8090162.

Barão, L. and Teixeira, R. (2015) "The environmental impacts of silicon as an alternative to phosphorus fertilizers What is the environmental impact of replacing P fertilizers with Si fertilizers?," *Eutrophication*, 11, 1730.

Bennett, S.J., Snell, R. and Wright, D. (2006) "Effect of variety, seed rate and time of cutting on fibre yield of dew-retted hemp," *Industrial Crops and Products*, 24, pp. 79–86. Available at: https://doi.org/10.1016/j.indcrop.2006.03.007.

Bócsa, L. and Karus, M. (1988) *The cultivation of hemp: botany, varieties, cultivation and harvesting*. Sebastopol: Hemptech.

Bócsa, I., Máthé, P. and Hangyel, L. (1997) "Effect of nitrogen on tetrahydrocannabinol (THC) content in hemp (*Cannabis sativa* L.) leaves at different positions," *Journal of International Hemp Association*, 4, pp. 78–79.

Campiglia, E., Radicetti, E. and Mancinelli, R. (2017) "Plant density and nitrogen fertilization affect agronomic performance of industrial hemp (*Cannabis sativa* L.) in Mediterranean environment," *Industrial Crops and Products*, 100, pp. 246–254. Available at: https://doi.org/10.1016/j.indcrop.2017.02.022.

Chandra, L.S. *et al.* (2011) "Temperature response of photosynthesis in different drug and fibre varieties of *Cannabis sativa* L.," *Physiology and Molecular Biology of Plants*, 17, pp. 297–303. Available at: https://doi.org/10.1007/s12298-011-0068-4.

Chinnasami, K.N. and Chandrasekaran, S. (1978) "Silica status in certain soils of Tamil Nadu," *Madras Agricultural Journal*, 65, pp. 743–746.

Coffmann, C.B. and Gentner, W.A. (1975) "Cannabinoid profile and elemental uptake of *Cannabis sativa* L. as influenced by soil characteristics," *Agronomy Journal*, 67, pp. 491–497.

Dilena, E. *et al.* (2023) "Investigating how nitrogen nutrition and pruning impacts on CBD and THC concentration and plant biomass of *Cannabis sativa*," *Scientific Reports*, 13, 19533. Available at: https://doi.org/10.1038/s41598-023-46369-5.

Evarte-Bundere, G. and Evarts-Bunders, P. (2012) "Using of the Hydrothermal coefficient (HTC) for interpretation of distribution of non-native tree species in Latvia on example of cultivated species of genus *Tilia*," *Acta Biologica Universitatis Daugavpiliensis*, 12(2), pp. 135–148.

Farnisa, M.M. *et al.* (2023) "Floral hemp (*Cannabis sativa* L.) responses to nitrogen fertilization under field conditions in the high desert," *PLoS ONE*, 18, e0284537. Available at: https://doi.org/10.1371/journal.pone.0284537.

Finnan, J. and Burke, B. (2013) "Nitrogen fertilization to optimize the green gas balance of hemp crops grown for biomass," *Global Change Biology Bioenergy*, 5, pp. 701–712. Available at: https://doi.org/10.1111/gcbb.12045.

Gill, A.R. *et al.* (2022) "Physiological and morphological responses of industrial hemp (*Cannabis sativa* L.) to water deficit," *Industrial Crops and Products*, 187, Part A, 115331. Available at: https://doi.org/10.1016/j.indcrop.2022.115331.

Gill, A.R.·*et al.* (2023) "The potential of industrial hemp (*Cannabis sativa* L.) as an emerging drought resistant fibre crop," *Plant and Soil*, 493, pp. 7–16. Available at: https://doi.org/10.1007/s11104-023-06219-9.

Grabowska, K. and Koziara, W. (2001) "Wpływ temperatury i opadów na plonowanie konopi włóknistych odm. Białobrzeskie [Effect on temperature and precipitation on yields of the *Cannabis sativa* variety Białobrzeskie]," *Natural Fibres*, 45, pp. 7–17.

Greger, M., Landberg, T. and Vaculík, M. (2018) "Silicon influences soil availability and accumulation of mineral nutrients in various plant species," *Plants*, 7, pp. 1–16. Available at: https://doi.org/10.3390/plants7020041.

Haney, A. and Kutscheid, B.B. (1973) "Quantitative variation in the chemical constituents of marihuana from stands of naturalized *Cannabis sativa* L. in east-central Illionis," *Economic Botany*, 27, pp. 193–203.

Hemphill, J.K., Turner, J.C. and Mahlberg, P.G. (1980) "Cannabinoid content of individual plant organs from different geographical strains of *Cannabis sativa* L. (*Cannabinaceae*)," *Journal of Natural Products*, 43, pp. 112–122.

Höppner, F. and Menge-Hartmann, U. (1995) "Cultivation experiments with two fibre hemp varieties," *Journal of International Hemp Association*, 2, pp. 18–22.

IUSS (2022) *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps*. 4th edn. Vienna, Austria: International Union of Soil Sciences.

Jaremko, D. and Kalembasa, D. (2014) "A comparison of methods for the determination of cation exchange capacity of soils," *Ecological Chemistry and Engineering S*, 21(3), pp. 487–498. Available at: https://doi.org/10.2478/eces-2014-0036.

Kannan, N.M. and Raj, S.A. (1998) "Occurrence of silicate solubilizing bacteria in rice ecosystem," *Madras Agricultural Journal*, 85, pp. 47–50.

Kaur, N. *et al.* (2023) "Nitrogen fertilization impact on hemp (*Cannabis sativa* L.) crop production. A review," *Agronomy Journal*, 115(4), pp. 1557–1570. Available at: https://doi.org/10.1002/agj2.21345.

Kim, J. *et al.* (2024) "Characterization of male flower induction by silver thiosulfate foliar spray in female *cannabis* at the middle reproductive stage for breeding," *Plants*, 13, 2429. Available at: https://doi.org/10.3390/plants13172429.

Komosa, A. and Stafecka, A. (2003) "Comparison of phosphorus, potassium, and magnesium contents determined with the universal, Egner-Riehm and Schachtschabel methods in orchard soils," *Folia Horticulturae*, 15(2), pp. 137–149.

Kostuik, J. and Williams, D.W. (2019) "Hemp agronomy–grain and fiber production," in J. Fike *et al.* (eds.) *Industrial hemp as a modern commodity crop*. Madison, WI, USA: American Society of Agronomy, Crop Science Society, pp. 59–72.

LI-COR Inc. Biosciences (2010) *LAI-2200 Plant canopy analyzer. Instruction Manual*. Lincoln, NE.

Lipson Feder, C. *et al.* (2021) "Fertilization following pollination predominantly decreases phytocannabinoids accumulation and alters the accumulation of terpenoids in *Cannabis* inflorescences," *Frontiers in Plant Science*, 12, 753847. Available at: https://doi.org/10.3389/fpls.2021.753847.

Lisson, S.N., Mendham, N.J. and Carberry, P.S. (2000) "Development of a hemp (*Cannabis sativa* L.) simulation model. General introduction and the effect of temperature on the pre-emergent development of hemp," *Australian Journal of Experimental Agriculture*, 40, pp. 405–411. Available at: https://doi.org/10.1071/EA99058.

Ma, J.F. and Yamaji, N. (2006) "Silicon uptake and accumulation in higher plants," *Trends in Plant Science*, 11, pp. 392–393. Available at: https://doi.org/10.1016/j.tplants.2006.06.007.

Meena, V.D. *et al.* (2014) "A case for silicon fertilization to improve crop yields in tropical soils," *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 84, pp. 505–518. Available at: https://doi.org/10.1007/s40011-013-0270-y.

Neu, S., Schaller, J. and Dudel, E.G. (2017) "Silicon availability modifies nutrient use efficiency and content, C:N:P stoichiometry, and productivity of winter wheat (*Triticum aestivum*)," *Scientific Reports*, 7, 40829. Available at: https://doi.org/10.1038/srep40829.

Papastylianou, P., Kakabouki, I., and Travlos, I. (2018) "Effect of nitrogen fertilization on growth and yield of industrial hemp (*Cannabis sativa* L.)," *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 46(1), pp. 197–201. Available at: https://doi.org/10.15835/nbha46110862.

Peltonen, J., Virtanen, A. and Haggren, E. (1995) "Using a chlorophyll meter to optimize nitrogen fertilizer application for intensively managed small-grain cereals," *Journal of Agronomy and Crop Science*, 174, pp. 309–318. Available at: https://doi.org/10.1111/j.1439-037X.1995.tb01118.x.

PN-R-04031:1997. *Analiza chemiczno-rolnicza gleby – Pobieranie próbek [Agricultural-chemical soil analysis – sampling]*. Warszawa: Polski Komitet Normalizacyjny.

Poniatowska, J. *et al.* (2019) "Contribution of Polish agrotechnical studies on *Cannabis sativa* L. to the global industrial hemp cultivation and processing economy," *Herba Polonica*, 65, pp. 37–50. Available at: https://doi.org/10.2478/hepo-2019-0012.

Poniatowska, J. *et al.* (2022) "Variability of cannabinoid yields of fibre hemp cultivars depending on the sowing density and nitrogen fertilization," *Plant Soil Environment*, 68(11), pp. 525–532. Available at: https://doi.org/10.17221/223/2022-PSE.

Poniatowska, J. *et al.* (2024) "The influence of sowing density and nitrogen fertilization on the yielding and main technological features of some hemp varieties," *Journal of Natural Fibers*, 21(1). Available at: https://doi.org/10.1080/15440478.2024.2433065.

Reithmaier, G.M.S. *et al.* (2017) "Enhanced silicon availability leads to increased methane production, nutrient and toxicant mobility in peatlands," *Scientific Reports*, 18, 8728. Available at: https://doi.org/10.1038/s41598-017-09130-3.

Rupasinghe, H.P.V. *et al.* (2020) "Industrial hemp (*Cannabis sativa* subsp. *sativa*) as an emerging source for value-added functional food ingredients and nutraceuticals," *Molecules*, 25, 4078. Available at: https://doi.org/10.3390/molecules25184078.

Saloner, A. and Bernstein, N. (2020) "Response of medical *cannabis* (*Cannabis sativa* L.) to nitrogen supply under long photoperiod," *Frontiers Plant Science, Section Plant Nutrition*, 11, 572293. Available at: https://doi.org/10.3389/fpls.2020.572293.

Saloner, A, and Bernstein N. (2022) "Nitrogen Source Matters: High NH_4/NO_3 Ratio Reduces Cannabinoids, Terpenoids, and Yield in Medical Cannabis," *Frontiers Plant Sciences*, Available at: https://doi.org/ 10.3389/fpls.2022.830224.

Schaller, J. *et al.* (2012) "Silicon supply modifies C:N:P stoichiometry and growth of *Phragmites australis*," *Plant Biology*, 14, pp. 392–396. Available at: https://doi.org/10.1111/j.1438-8677.2011.00537.x.

Sengloung, T., Kaveeta, L. and Nanakorn, W. (2009) "Effect of Sowing Date on Growth and Development of Thai Hemp (*Cannabis sativa* L.)," *Agriculture and Natural Resources*, 43, pp. 423–431.

Song, M.H. *et al.* (2012) "Different inter-annual responses to availability and form of nitrogen explain species coexistence in an alpine meadow community after release from grazing," *Global Change Biology*, 18, pp. 3100–3111. Available at: https://doi.org/10.1111/j.1365-2486.2012.02738.x.

Song, Z.L. *et al.* (2014) "Ecological stoichiometry of N:P:Si in China's grasslands," *Plant Soil*, 380, pp. 165–179. Available at: https://doi.org/10.1007/s11104-014-2084-y.

Struik, P.C. *et al.* (2000) "Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe," *Industrial Crops and Products*, 11, pp. 107–118. Available at: https://doi.org/10.1016/S0926-6690(99)00048-5.

Struyf, E. *et al.* (2010) "Historical land use change has lowered terrestrial silica mobilization," *Nature Communications*, 1, 129. Available at: https://doi.org/10.1038/ncomms1128.

Swora-Cwynar, E., Gała, P. and Łata, M. (2025) "Hemp in Poland – the importance of social communication and health education in using the plant's potential in medicine, economy and agriculture – current status," *Przegląd Epidemiologiczny – Epidemiological review*, 79(1), pp. 1–37. Available at: https://doi.org/10.32394/pe/203854.

Tang, K. *et al.* (2017) "Hemp (*Cannabis sativa* L.) leaf photosynthesis in relation to nitrogen content and temperature: implications for hemp as a bio-economically sustainable crop," *Global Change Biology Bioenergy*, 9, pp. 1573–1587. Available at: https://doi.org/10.1111/gcbb.12451.

Teleszko, M., Zając, A. and Rusak, T. (2022) "Hemp seeds of the Polish 'Bialobrzeskie' and 'Henola' Varieties (*Cannabis sativa* L. var. *sativa*) as prospective plant sources for food production," *Molecules*, 27, 1448. Available at: https://doi.org/10.3390/molecules27041448.

TIBCO Software Inc. (2017) *Statistica (Data Analysis Software System) ver. 13*. [Computer program]. Available at: https://docs.tibco.com/products/tibco-statistica-document-management-system-13-3-1 (Accessed: October 10, 2024).

Upton, R. *et al.* (2013) *American herbal pharmacopeia: Cannabis inflorescence: Cannabis spp: Standards of identity, analysis, and quality control.* Scott's Valley, CA: American Herbal Pharmacopoeia.

Wawro, A., Batog, J. and Gieparda, W. (2021) "Polish varieties of industrial hemp and their utilisation in the efficient production of lignocellulosic ethanol," *Molecules*, 26(21), 6467. Available at: https://doi.org/10.3390/molecules26216467.

Wee, Y.B. *et al.* (2025) "Same, yet different: towards understanding nutrient use in hemp- and drug-type *Cannabis*," *Journal of Experimental Botany*, 76(1), pp. 94–108. Available at: https://doi.org/10.1093/jxb/erae362.

Xu, D. *et al.* (2020) "Silicon addition improves plant productivity and soil nutrient availability without changing the grass: legume ratio response to N fertilization," *Scientific Reports*, 10, 10295. Available at: https://doi.org/10.1038/s41598-020-67333-7.

Zdaniewicz, M. *et al.* (2024) "Characteristics of selected bioactive compounds and malting parameters of hemp (*Cannabis sativa* L) seeds and malt," *Molecules*, 29, 4345. Available at: https://doi.org/10.3390/molecules29184345.

Zielonka, D. *et al.* (2017) "Efficiency of the photosynthetic apparatus in *Cannabis sativa* L. fertilized with sludge from a wastewater treatment plant and with phosphogypsum," *Ecological Questions*, 28, pp. 55–61. Available at: https://doi.org/10.12775/EQ.2017.039.

Żuk-Gołaszewska, K. (2008) "*Produkcyjność i produktywność jęczmienia jarego (Hordeum vulgare L.) uprawianego w różnych warunkach agrotechniki" [Productivity and productiveness of spring barley (Hordeum vulgare L.) cultivated in different agrotechnical conditions]. Rozprawy i Monografie*, 136. Olsztyn: Uniwersytet Warmińsko-Mazurski w Olsztynie.

Żuk-Gołaszewska, K. and Gołaszewski, J. (2018) "*Cannabis sativa* L.: cultivation and quality of raw material – review," *Journal of Elementology*, 23, pp. 971–984. Available at: https://doi.org/10.5601/jelem.2017.22.3.1500.

Żuk-Gołaszewska, K. and Gołaszewski, J. (2020) "Hemp production," in G. Crini and E. Lichtfouse (eds.) *Hemp production and applications. Sustainable agriculture, Reviews*, 42. Cham: Springer Nature, pp. 1–36. Available at: https://doi.org/10.1007/978-3-030-41384-2_1.