

Article

Fiber Hemp Biomass Yield and Quality on Shallow Stony Soil in Southwest Germany

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Abstract: Shallow arable soils (<35 cm depth) are classified as marginal for common agriculture but may still support biomass production from industrial crops like fiber hemp, which has a low indirect land-use change risk. However, little is known about hemp's performance under such conditions. Therefore, this study investigated the biomass yield and quality of fiber hemp and other crops on a shallow (<35 cm), stony (>15% stone content), and clay-rich (>50% clay content) soil at 800 m above sea level in Southwest Germany (2018–2021). A randomized field trial tested different row widths and nitrogen (N) fertilization levels to assess low-input options for the given type of marginal land. Across years and row widths, hemp achieved average grain dry matter (DM) yields of 1.3 Mg/ha at a fertilization rate of 40 kg N/ha and 1.6 Mg/ha at 120 kg N/ha (with on average $30.9 \pm 1.4\%$ crude fat content across treatments). The average stem DM yields accounted for 5.11 Mg/ha (40 kg N/ha) and 6.08 Mg/ha (120 kg N/ha), respectively. Reduced N fertilization (40 kg/ha) lowered DM yields by up to 16% compared to full fertilization (120 kg/ha), but the effect was not significant and weaker at wider row spacing (45 cm). Additionally, maize reached acceptable DM yields (>17 Mg/ha). These findings suggest that shallow soils classified as marginal require reassessment, as they may offer viable opportunities for sustainable industrial hemp cultivation and contribute to a bio-based economy.

Keywords: industrial hemp; marginal land; low-input conditions; row width; nitrogen fertilization



Academic Editor: Cezary Kabala

Received: 27 February 2025

Revised: 15 March 2025

Accepted: 24 March 2025

Published: 27 March 2025

Citation: Greiner, B.E.; Kunisch, J.; Krauße, G.; Thiel, T.; Schwadorf, K.; von Cossel, M. Fiber Hemp Biomass Yield and Quality on Shallow Stony Soil in Southwest Germany. *Land* **2025**, *14*, 720. <https://doi.org/10.3390/land14040720>

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1. Introduction

The industrial era, while fueling growth, has led to multiple unprecedented challenges [1]. These challenges are, among others, an increased demand for various resources such as water, food, energy and other materials, massive biodiversity losses, habitat loss, and environmental degradation [1]. These issues are reflected in the 16 Sustainable Development Goals (SDGs), implemented by the United Nations in 2015 to create inclusive and transparent goals for a better future [1]. At the European level, a similar but smaller scale set of goals are laid down in the European Bioeconomy Strategy [2].

The idea of bioeconomy is to replace fossil-based raw materials and move towards a bio-based economy, thereby counteracting issues resulting of ongoing global warming events and the anthropogenic overexploitation of resources [3]. The following goals of the European Bioeconomy Strategy depict this vision:

- Ensure food and nutrition security;
- Manage natural resources sustainably;

- Reduce dependence on non-renewable, unsustainable resources;
- Limit and adapt to climate change;
- Strengthen European competitiveness and create jobs [4].

Goal number 1, to ensure food and nutrition security, is especially relevant when looking at planetary boundaries while considering the population development of the subsequent years. Every year, the population worldwide is growing by approximately 83 million people, which equals the population of Germany [5]. In 2030, the global population is estimated to grow to 8.5 billion [5]. With that said, demands for food and energy will rise significantly. According to the United Nations UN World Water Development Report 2012 [6], an additional 50% of food, 50% of energy, and 30% of fresh water is going to be needed to fulfill the basic needs of the population. Goal number 1, together with the bioeconomic goal of achieving a bio-based system, might further heat the food versus fuel debate. This was seen, for example, in the US, after the increased cultivation of maize (*Zea mays* L.) for ethanol production led to food scarcity and a subsequent food price crisis in 2007 and 2008 [1]; this was also seen in Germany, after a drastic increase in maize cultivation for biogas production [7].

The globally dependent use of fossil resources is not a reliable solution for a sustainable future [2]. A wide range of possibilities for overcoming current challenges lies in the substitution of fossil resources through the provision of biomass from land-based plants (hereafter referred to as ‘industrial crops’). One promising industrial crop is fiber hemp (*Cannabis sativa* L.), renowned for its versatility in producing bio-based materials [8–10].

Hemp has palmate leaves, the edge of which is serrate. The male flower appears loosely in panicles, while the female flower is arranged in clusters. Hemp seeds are small nuts, which have a diameter of about 3 mm. Its historical use does not differ from how it is used today: for medical purposes, as a textile fiber, oil, and food [11]. These multiple application possibilities are due to hemp’s abundant range of phytochemicals and its strong fibers [8,12]. Being a multifunctional crop, *C. sativa* has a high market potential, especially within the industrial and medical use [13,14].

Within the bioeconomy, the debate about industrial crops is highly relevant as crops like fiber hemp are the cornerstone of bioenergy and many high added-value bio-based commodities [15,16]. With the biomass feedstocks that are made available through their growth on marginal lands, products such as bio-based pharmaceuticals, bio-plastics, bio-chemicals, bio-composites, and bio-lubricants can be generated to guarantee their spot in replacing the equal yet fossil-based products [15,16]. However, there is broad consensus within the biomass community that industrial crops should not compete with food production for arable land [17–19]. To avoid land-use conflicts and reduce the risk of indirect land-use changes, marginal arable lands—those characterized by poor soil quality or other biophysical limitations—are considered ideal for industrial crop cultivation [20,21]. Utilizing such lands could play a crucial role in advancing the European bioeconomy and enabling the sustainable production of biomass without displacing food crops [22,23]. Unlike other crops that compete with food production, fiber hemp can grow on this marginal arable land. This makes fiber hemp well-suited for advancing the bioeconomy while reducing the need for fertile land.

Since there are many different types of marginal arable land [24], the question is where fiber hemp could be grown successfully to provide the processing fiber industries with sufficient biomass in the long term. On top, being an annual crop, fiber hemp would also require enough area within the region of interest to allow for a wide crop rotation with other annual or biennial non-edible industrial crops such as crambe (*Crambe abyssinica* R.E.Fr.) and yellow melilot (*Melilotus officinalis* L.) [16,25]. Only then, the provision of biodiversity-friendly biomass could be realized [26,27]. It would, therefore, make the most sense to

look at the most frequently available type of marginal arable land to further assess the overall suitability of fiber hemp as a biomass provider of the future bioeconomy. Following Von Cossel et al. [28], adverse rooting conditions such as shallow and/or stony soil are the major types of marginal arable land in Europe. The rooting depth that determines an agricultural land as marginal, varies within the literature and describes soil depth values between <35 cm to <50 cm [29,30]. In the growth and developmental stages of plants, a low rooting depth is detaining [31,32]. An adequately developed, deep rooting system is essential, especially in terms of optimizing the plant's adaptation to its environment as well as its achieving biomass yield [31,32].

Selecting marginal arable land, characterized by shallow and stony soils, as a cultivation site for fiber hemp, presents challenges. Additionally, introducing low-input agricultural practices adds an extra layer of difficulty, but it also has the potential to make the cropping system even more sustainable, aligning with the goals of a socially and ecologically friendly European bioeconomy [10]. Marginal arable land low-input systems contribute to a production of biomass that will have regard to social-ecological threats associated with an increased production of biomass [33]. A higher use of fertilizers and pesticides is one of these threats [34]. The application of high amounts of fertilizers, pesticides, and other high-input production systems may lead to high yields but will lead to the consequence of an unsustainable environment that is continuously in need of diminishing resources [35]. Marginal arable land low-input systems, however, incorporate good agricultural practices into its systems, which in regard to fertilizer application means “to replace only the amount of nutrients that were extracted by harvest” [36], as cited in Von Cossel et al. [10]. Resource-use efficiency becomes particularly crucial in such contexts, where the natural yield potential and resilience of the ecosystem are already lower compared to fertile lands. [26,37–39]. Thus, to implement a low-input system on marginal arable land, Biala et al. [40] states that off-farm inputs (e.g., energy inputs) should be reduced, and on-farm inputs should be increased. Low-input agricultural systems thereby lead to an adequate output supply with minimal input requirements [35,40–42]. Its implementation respects environmental aspects as well as socio-economic issues, by ensuring a feasible economic use of land that was priorly not used due to its biophysical limiting factors [10].

Given this background, the research objective of this study was to determine whether and how fiber hemp can be successfully cultivated on shallow stony soils in Southwest Germany with particular focus on its phenological development, biomass yield, and quality performance. Therefore, the study examines the influence of varying fertilization levels and row spacing on hemp growth. The results aim to contribute to a growing understanding of how hemp could serve as an industrial crop on marginal land types, supporting the transition from a fossil-based to a bio-based European economy.

2. Material and Methods

2.1. Experimental Site and Field Trial Design

A field trial (randomized block design, $n = 3$, net plot size: 6 m × 6 m) was carried out in frame of the EU Horizon 2020 Project MAGIC at the experimental station “Oberer Lindenhof” in Eningen unter Achalm in Germany during the years 2018–2021. The field site lies at an altitude of 720 m a.s.l. (meters above sea level) and is located adjacent to a forest and a steep slope on the edge of the Swabian Alb Plateau with a height difference of 340 m (48°28′15.0″ N 9°18′05.8″ E). The soil type is rendzina on limestone.

2.2. Climatic Conditions

Over the past four years, the recordings showed a mean temperature of 8.52 °C and an average yearly precipitation sum of 858.2 mm. In 2018, the recorded precipitation

amounted to 605.7 mm, and the mean temperature recorded was 9.1 °C. Additionally, the global radiation for that year was at 1303 kWh/m². The year 2019 was the year with the highest recorded precipitation at 1074.7 mm. The mean temperature in that year amounted to 8.6 °C, and the recorded global radiation equaled 1244 kWh/m². In 2020, the total precipitation reached 819.3 mm, the mean temperature was 8.9 °C, and the global radiation added up to 815 kWh/m². Finally, in year 2021, the yearly precipitation equaled 933.1 mm, while the mean temperature was 7.5 °C, and the global radiation amounted to 1286 kWh/m². A detailed surveillance of the temperature and precipitation values are depicted in Table 1. The weather data were acquired from a weather station located at Oberer Lindenhof.

Table 1. Weather data (precipitation, temperature, and global radiation) obtained from the weather station at Oberer Lindenhof (available at: www.wetter-bw.de (accessed on 3 August 2022)). Sum (Σ) and means ($\bar{\phi}$) of years 2018–2021.

Year	2018	2019	2020	2021
Precipitation sum (mm)	605.7	1074.7	819.3	933.1
Average temperature 2 m above soil (°C)	9.1	8.6	8.9	7.5
Global radiation (kWh/m ²)	1303	1244	815	1286

2.3. Sowing

Hemp was sown with a Haldrup sowing machine (Figure 1a–c) at a sowing density of 20 kg/ha.

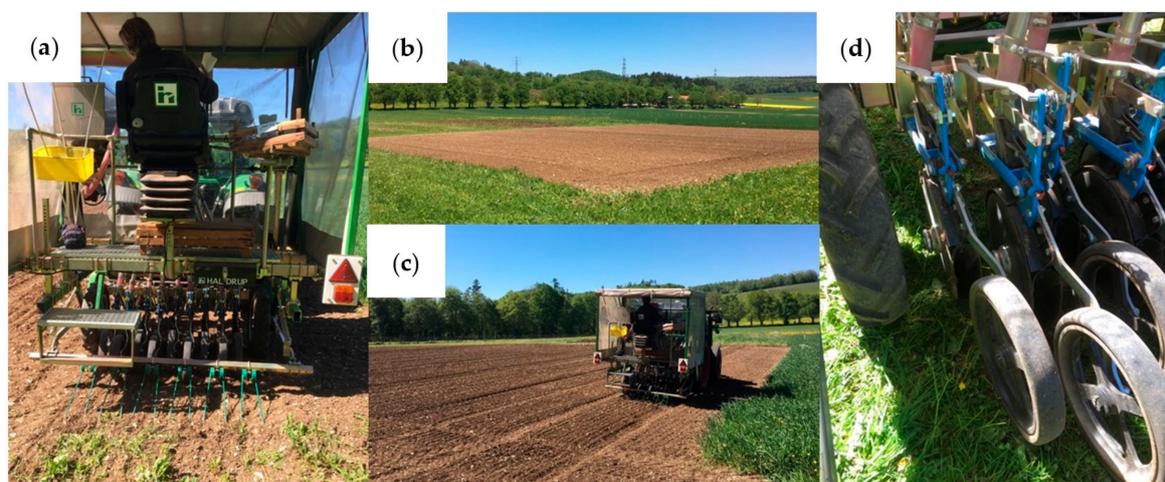


Figure 1. Impressions of one of the sowing events at Oberer Lindenhof (May 2021): the Haldrup sowing machine (a), which was used to sow the hemp seeds; the cultivation site before (b) and during sowing (c); and the disc coulters of the sowing machine (d).

The approximate depth was 5 cm. The space between the rows of seeds is 13.5 cm. This was achieved with the help of disc coulters (Figure 1d), which make the process easier than drag coulters due to the stony and flat soil conditions at the site. The latter would come into continuous contact with the stones and be damaged as a result. In addition to hemp, maize was grown as a reference crop (2019–2021). Camelina and calendula were also grown in the field trial. However, for the purpose of this study, only hemp and the reference crop maize were considered for analysis.

2.4. Fertilization Strategy

To analyze the effect of fertilizer on fiber hemp, different levels of fertilizer were applied in all four years. They are depicted in Table 2.

Table 2. N Fertilizer levels used throughout the years at Oberer Lindenhof.

Year	N Fertilizer Levels
2018	0 kg, 40 kg, 80 kg, 120 kg
2019	40 kg, 120 kg
2020	40 kg, 120 kg
2021	40 kg, 120 kg

2.5. Row Distance

A second experimental factor was used for the quantitative and qualitative study. This experimental factor was characterized by two different row spacings, which were applied together with all fertilization levels (except for 0 kg N and 80 kg N, which were only applied on plots with 15 cm row width). The row spacings of 15 cm and 45 cm were investigated, as it was intended to analyze whether the stand density influences the quantitative and qualitative results. The row spacing was maintained with the help of disc coulters at sowing time.

In total, the row distance and fertilization levels created four different treatment types for hemp.

2.6. Qualitative and Phenological Analysis Approach

2.6.1. Soil Sample Collection and Soil Depth Determination

For the analysis within this study, soil samples of the years 2020 and 2021 are provided. The soil sample extraction in 2020 was performed on the 4th of May. In 2021, two different, time separate samples were taken. The first soil samples were collected on 21st of May 2021, before the sowing of hemp. After the harvest on the 9th of November 2021, the second set of soil samples was taken. For the procedure in May 2020 and 2021, a soil auger was used for the samples. After collecting the samples in freezer bags, the soil samples were transported back to the university where they were analyzed following standard procedures for the parameters shown in Figure 2.

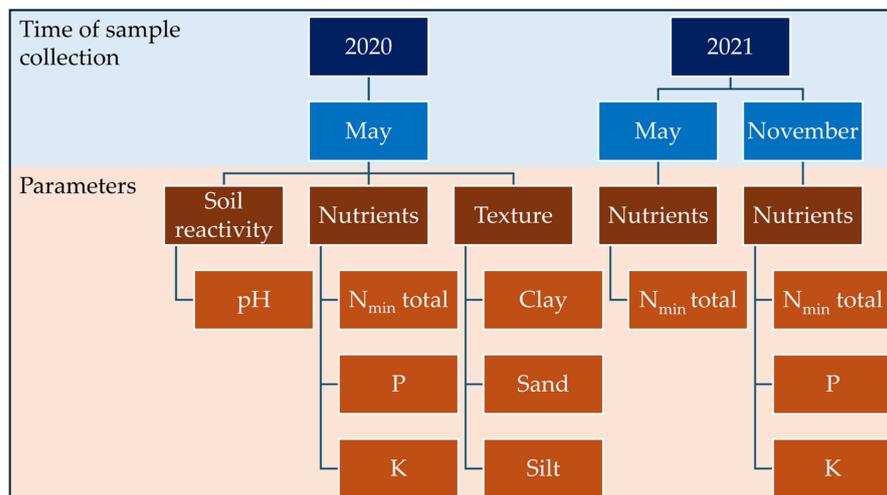


Figure 2. Overview of soil parameters analyzed during the field trial.

The stone content of the soil at Oberer Lindenhof was measured on the 9th of November 2021. In the past the stone content was based on estimations solely. Based on the available materials, the experimental set up consisted of a spade (measuring 17 cm in width and 18 cm in length), a 2 liter measuring cup, a sieve (6 mm mesh width), as well as water and two containers. The average length, width, and depth of the hole was ~23.1 cm, ~21.2 cm, and ~17.6 cm, respectively.

Using a spade, a square shaped hole was created within one of the two middle rows of a plot. After digging the soil up and transporting it into one of the containers, the soil was sieved to separate stones and pure soil. The stones were transferred into the measuring cup, which was then filled up with water to the 2 liter mark. Next, the water volume without the stones was measured, thereby giving details on the volume the stones amount to (Figure 3). The method of isolating the stones to determine stone content of the soil, was based on the material available and the limiting factors of the soil (a hard rock layer surface at about 20 cm of depth).

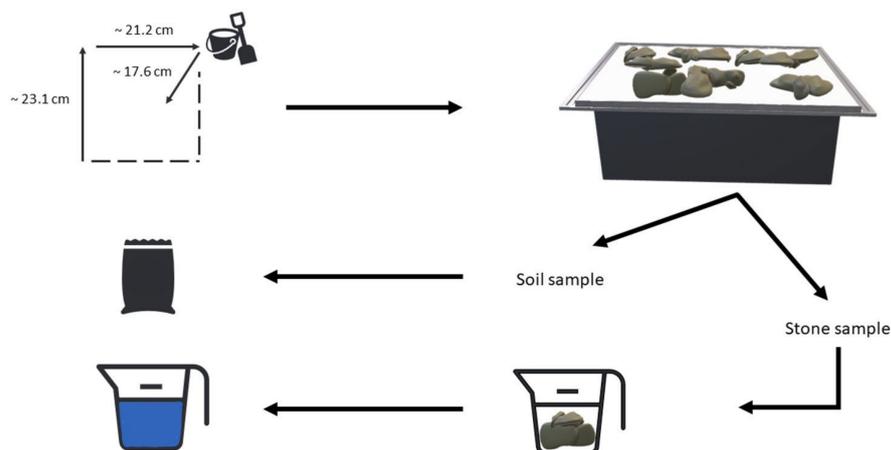


Figure 3. Method of determining the stone content.

2.6.2. Fatty Acid Content and Pattern

To determine the fatty acid pattern of grain samples from harvest years 2018–2020, a capillary gas chromatography following the TMSH (trimethylsulfonumhydroxide) method was performed. This method conducts a quantitative gas chromatography determination of the total fatty acid spectrum by displaying the fatty acid methyl esters (FAME) from fats and/or oils. The principle of the method is depicted in the following steps:

- Dissolution of present oil sample in diisopropyl ester;
- 0.2 M trimethylsulfonumhydroxide in methanol is added, which induces the methylation of the oil sample;
- The created solution is then used to perform the capillary gas chromatography.

The results of the capillary gas chromatography following the TMSH method are evaluated using the 100% method, which signifies that the content of methyl ester is determined by calculating the percentage equivalent to its peak area relative to the total amount of all FAME peak areas included in the chromatogram. The calculated outcome is demonstrated in percentage relative to the total fatty acids.

2.6.3. Root Morphology

The study by von Cossel et al. [28] suggests hemp to be unsuitable for the soil depth class “shallow”, which accounts to a depth of <35 cm. Cultivation despite this knowledge suggests adaptation of the root system. Consequently, hemp was harvested on the 18 October 2021 with its root system to study it in more detail (Figure 4a,b). Phenological observations were made (visual comparison to hemp roots grown in non-shallow soil), and quantitative values (biomass fraction, dry matter yield) were collected.

To make these observations, the hemp roots were separated from the stems and then weighed while still in the field to determine the fresh mass. The next step involved washing the roots thoroughly. Figure 4 shows the effect of washing. The roots were, thereafter, dried in a drying oven at 60 °C degrees for 24 h. The next day, the root samples were reweighed

to determine the dry matter yield value. The root samples were afterwards ground to make them suitable for further investigations in the laboratory. The laboratory results will not be included in this study.



Figure 4. Hemp roots directly after harvesting the whole plant (a), and hemp root separated from its stem and washed thoroughly (b).

2.6.4. Stand Density

The stand density of hemp was measured to capture possible losses during field emergence, self-thinning effects, and due to weather impacts. To calculate the values for self-thinning, it was fundamental to determine the stand density one time after field emergence and the second time before crop harvest.

The stand density was determined by using a folding rule, which was arranged to form a square of 0.36 m^2 . This square was then put into each of the two inner rows of the plot and the plants contained within the frames were counted (Figure 5).

Thus, two values per plot were collected and used to calculate the mean value of plants per 0.36 m^2 . This value was then extrapolated to obtain the number of plants per m^2 . The initial 0.36 m^2 and the folding rule were used to acquire a representative sample of the plot, thereby not including the outer two plant rows of each plot row.



Figure 5. Stand density measured after field emergence on 30 June 2021. The plants were measured using a folding rule, creating a space of 0.36 m^2 .

2.6.5. Self-Thinning Calculation

Self-thinning was calculated with stand density values. Self-thinning reveals whether successful plant development has taken place [43].

The self-thinning value (SA) indicates how many plants died during the growing period [44]. This value can be influenced by environmental conditions, such as weather. According to Schöberl et al. [44], this phenomenon was first introduced by two researchers in 1995 and can especially be observed in hemp [45]. The self-thinning value is calculated using the following Equation (1) by Schöberl et al. [44].

$$SA = \left(1 - \left(\frac{BD2}{BD1} \right) \right) \times 100 \quad (1)$$

BD1 = stand density 1 (two-leaf stage) in plants/m². BD2 = stand density at harvest.

2.6.6. Growth Stages Determination

Starting from the 30 June 2021, the growth of hemp and maize was determined each week to establish a clear picture of the unique development of them as well as to potentially observe intraspecific differences resulting of different fertilization strategies and row distances. The assessment was performed by taking one randomly selected sample out of each of the four plot rows to have a representative sample of plants leading to a determination representative of the whole plot. Additionally, pictures were taken of each growth stage, general observations of the population were noted, and animal sightings were registered. The growth stages for hemp were determined according to the literature standards [1].

In order to depict the phenological development of maize and hemp the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale was used. The BBCH scale consists of ten macro growth stages, which are the same for all dicotyledonous and monocotyledonous species [46,47]. These macro growth stages are listed in Table 3.

Table 3. Macro BBCH stages as described by [47,48].

Stage	Description
0	Germination
1	Leaf development (main shoot)
2	Growth in length (main shoot), tillering
3	Stem elongation
4	Booting
5	Inflorescence emergence, heading
6	Flowering
7	Development of fruit
8	Ripening of fruit and seeds
9	Senescence

Generally, only the phenological development of the main shoot is described using the macro stages that are represented using digits in ascending order from 0 to 9 [47]. This subdivision in ten parts creates manageable and clearly distinguishable development phases [47]. Yet, these macro growth stages are not expected to take place in the strict hierarchical order that Table 3 might imply. The growth stages can also run parallel to each other [47]. On the other hand, the so-called micro stages are used whenever more precise stages of development are required [47]. The micro stages are short development steps that are characteristic to the respective plant and are depicted using the digits 0–9 as well [47]. Together, the digits of the macro and micro growth stages result in a two-digit BBCH code, which generates a precise collection of all phenological development stages [47].

Regarding hemp, the assessment of growth stages during the flowering period became more extensive as hemp plants show differences in development based on either their monoecious or dioecious nature. Whether a hemp plant is dioecious or monoecious depends on the variety [49]. The variety of this study, Markant, is a dioecious variety, meaning it produces either male or female flowers. Because of this, a BBCH coding system of Mediavilla et al. [49] was used as it is adapted to hemp's unique development and was approved by the International Hemp Association [49]. The phenological development of hemp consists of four main growth stages (Table 4) [49]. Each main growth stage is indicated with a digit ranging from 0 to 3 [49].

Table 4. Main growth stages of hemp (adapted from [49,50]).

Stage	Description
0	Germination and emergence
1	Vegetative stage
2	Flowering and seed
3	Senescence

The secondary growth stages are described using a second digit, which give information on the gender or the monoecious character of the plant [49]. The third and fourth digits finally describe the precise development stage [49]. The main turnover stages are shown in Table 5.

Because of self-thinning [45] and the monoecious/dioecious character of hemp, the literature suggests a sample size of 30 plants within plot trials [49]. However, as already mentioned above, in this study, only four representative plants for each plot were used.

Table 5. Turnover growth stages of hemp. Sources: [49,50].

Stage	Description
0002	Emergence of hypocotyl
2000	GV point
2102	Flowering staminate flower
2202	Flowering female flower
2302	Monoecious flowering
2204 or 2306	Seed maturity

2.6.7. Height Measurements

The height of all crops was measured on a two-week basis. Every fortnight one representative plant of each four plot rows was measured by using a folding rule. Having measured four values for each plot, the average height could be calculated.

2.7. Quantitative Analysis of the Results

2.7.1. Harvest

Harvesting of fiber hemp took place on the dates and according to the sample areas listed in Table 6. The harvest was a hand harvest with rose shears.

During the harvest, the entire plant was harvested and then weighed directly to obtain the FM sample area value. Then, a sub-sample was taken, and seeds and leaves were separated from the stems. Leaves and seeds were then placed in a separate bag and weighed. The same was applied for the stems. All values measured on-site during harvest are demonstrated in Table 7.

Table 6. Harvest dates and sample areas for years 2018–2021.

Harvest Date	Row Distances	Number of Rows	Row Width	Row Length	Sample Area
20 September 2018	15 cm	4, 5, 9	0.15 m	1 m	0.56 m ² , 0.7 m ² , 1.26 m ²
20 September 2018	45 cm	1	0.45 m	3 m	1.35 m ²
2 October 2019	15 cm	2	0.15 m	1 m	0.28 m ²
2 October 2019	45 cm	2	0.45 m	1 m	0.9 m ²
1 October 2020	15 cm	8 (2 × 4)	0.15 m	0.5 m	0.6 m ²
1 October 2020	45 cm	2 (2 × 1)	0.45 m	1 m	0.9 m ²
18 October 2021	15 cm	1	0.15 m	1 m	0.15 m ²
18 October 2021	45 cm	4	0.45 m	0.5 m	0.9 m ²

Table 7. Measurements taken on-site during all four harvests of hemp. “x” indicates that a value for this parameter was measured (FM = fresh matter).

Year	Height	Number of Plants	FM Sample Area	FM Weight Grain	FM Weight Stem	FM Weight Grain and Leaves	FM Weight Roots
2018	x	x	x	x	x		
2019	x	x	x	x	x		
2020	x	x	x	x	x		
2021	x	x	x		x	x	x

2.7.2. Deviations

In 2021, additionally to stems, grains, and leaves, hemp roots were also harvested, weighed, and further analyzed. Additionally, stem width measurements were taken.

2.7.3. Post-Harvest Procedures

After 24 h in the drying cabinet at 60 °C, grains were separated from leaves. Subsequently, in all four years, the samples were weighed again to produce the following results applying the following Equations (2)–(5):

$$\text{Grain DM yield} = \left(\frac{\left(\frac{10,000}{\text{Sample area}} \right)}{\text{Grain DM weight}} \right) \times \left(\frac{\text{Number of plants}}{\text{Plants per subsample}} \right) \quad (2)$$

$$\text{Stem DM yield} = \left(\frac{\left(\frac{10,000}{\text{Sample area}} \right)}{\text{Stem DM weight}} \right) \times \left(\frac{\text{Number of plants}}{\text{Plants per subsample}} \right) \quad (3)$$

$$\text{Leaves DM yield} = \left(\frac{\left(\frac{10,000}{\text{Sample area}} \right)}{\text{Leaves DM weight}} \right) \times \left(\frac{\text{Number of plants}}{\text{Plants per subsample}} \right) \quad (4)$$

$$\text{Roots DM yield} = \frac{\left(\left(\frac{10,000}{\text{Sample area}} \right) \times \text{Roots DM weight} \right)}{1,000,000} \quad (5)$$

2.8. Statistical Analysis

For this study, a mixed model approach was used with the statistical software SAS version 9.4 (SAS Institute, Cary, NC, USA). The experimental design was a randomized complete block design for all years except 2019. There were ten treatments with three replications each in 2020 and six treatments with three replications each in 2018 and 2021. In 2019, the experimental design was a completely randomized design with ten treatments and three replications each. The residuals were looked at and checked on their normality and homogeneity of variance. After that, a multiple mean comparison was performed. The

confidence level was set to 95%; thus, all p -values below 0.05 were considered statistically significant. To visualize this, a letter display was generated by the %MULT macro by [51]. Within the letter display, means with at least one identical letter indicated non-significance differences. Fertilization, row width, and row width \times fertilization were considered fixed effects. Furthermore, the three interaction effects row width \times year, fertilization \times year and row width \times fertilization \times year, as well as the year on itself, were regarded as random. In 2018, only one row width was applied for the fertilization levels 0 and 80 kg N. Therefore, an estimate statement was used for the statistical analysis of hemp, which calculated exactly the mean value when excluding the 0 and 80 kg N without allowing any data to go unused. This was performed by introducing another variable, acting as a dummy variable. Thus, missing data were assigned a 0, while the data to be analyzed were represented by a 1. All figures were generated using either SAS statistical software version 9.4 (SAS Institute, Cary, NC, USA) or Excel 2020 (Microsoft Corporation, Washington, DC, USA).

3. Results

3.1. Soil Characteristics

The soil analysis revealed a high content of clay and silt as well as a relatively high soil pH (Table 8) given that the site was cultivated with grassland in recent years (lower pH was expected). The soil N_{\min} was moderately high in both years of observation. In 2020, the soil content of potassium was moderate, and the soil content of phosphorus was high according to common nutrient content classes for arable land and grassland (Table 8).

Table 8. Soil texture composition and contents of NO_3 , NH_4 , N_{\min} total, soil depth, K_2O , P_2O_5 , and pH level at the site.

Year	Texture (in %)			NO_3 -N (kg/ha)	NH_4 -N (kg/ha)	N_{\min} total (kg/ha)	K_2O (mg/100 g Soil)	P_2O_5 (mg/100 g Soil)	pH
	Clay	Sand	Silt						
2020	43.7	12.2	44.1	43.5	22.9	66.4	15.8	46.6	7.2
2021	-	-	-	53.5	9.1	62.7	-	-	-

3.2. Qualitative and Phenological Analysis

For all parameters no significant effect of the interaction row width \times fertilization was observed (Table 9). Row width had a significant effect on plant height, and fertilization had a significant effect on grain dry matter (DM) yield (Table 9).

Table 9. Results of the type 3 tests with fixed effects ($Pr > F$).

Effect	Plant Height	Stand Density	Stem DM	Grain DM	Crude Fat
Row width	0.0412	0.0645	0.2136	0.9178	0.5896
Fertilization	0.1832	0.9655	0.2306	0.072	0.3588
Row width \times Fertilization	0.3693	0.532	0.2892	0.453	0.8468

3.2.1. Stem Width Observations

The stem width of hemp is an essential quality factor for fiber hemp production because the stem is suitable for textile production depending on the width. Hall et al. [52] assumes that finer stems provide higher quality for application in the textile industry. The measurements show that there is no statistically significant difference in stem width between fertilization with 40 (0.74 mm) and 120 kg N (0.69 mm). However, stem width is significantly ($p = 0.0025$, $\alpha = 0.05$) higher in the 45 cm row width (0.86) than in the 15 cm row width (0.58).

With row width \times fertilization, all treatments for hemp (treatments 1–4) were additionally compared with each other in SAS as opposed to fertilization and row width as individual parameters. As a result, treatment 3 (40 kg N–45 cm) resulted in the highest stem width with a mean value of 0.9333 cm. The lowest stem width was from treatment 1 (40 kg N–15 cm) with 0.55 cm. The performed significance test indicates a statistical significance between the measured values of treatment 2 (15 cm–120 kg N) and 3 (45 cm–40 kg N) with $p = 0.009$, treatment 1 (15 cm–40 kg N) and 4 (45 cm–120 kg N) with $p = 0.0431$ and treatment 1 and 3 ($p = 0.0043$).

3.2.2. Fatty Acid Content Analysis

The results of the analysis of the fatty acid pattern of hemp (Figure 6) show that the proportion of fatty acids is structured the same despite different fertilization levels and row spacing. The largest proportion is made up of α -linolenic acid, linoleic acid, and crude fat. A high proportion of these fatty acids is especially important in hemp, as hemp oil has a reputation as an omega-3-containing oil, of which α -linolenic acid is the source.

To find out whether fertilization levels, row width, or the interaction row width \times fertilization has an influence on the proportion of the two important fatty acids, the data were analyzed with proc mixed in SAS. Results of α -linolenic acid with $p = 0.6490$ show that there is no statistically significant difference in fertilization between the two levels. This is also reflected in the mean values, which differ by only a few percent: 15.25% at 120 kg N and 15.04% at 40 kg N (Figure 7). With regard to row width, the effect is the same. Row width as well as row width \times fertilization interaction also do not affect the amount of α -linolenic acid. Fertilization and row width, in any combination, thus, have no effect on the proportion of α -linolenic acid in hemp oil.

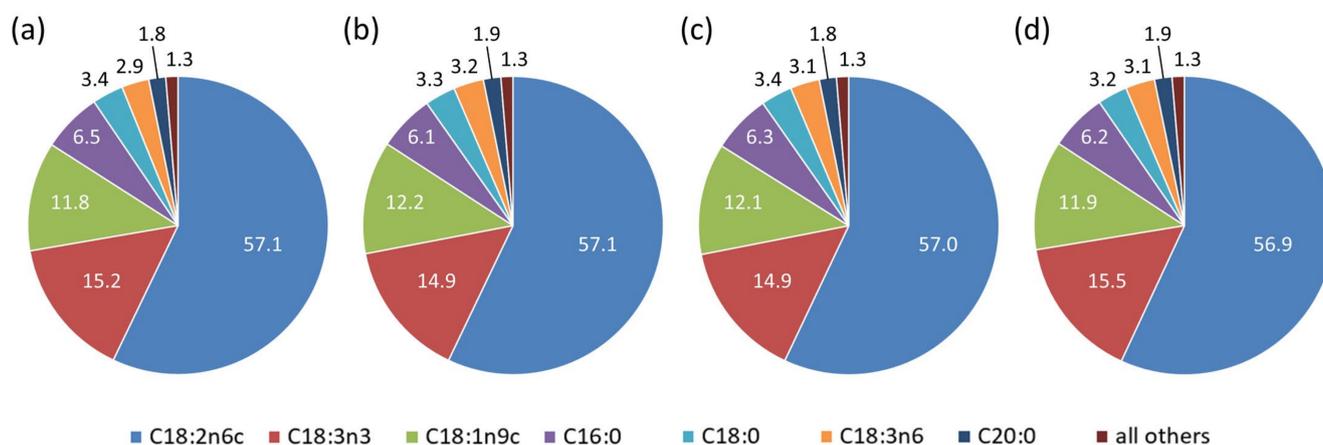


Figure 6. Fatty acid composition of hemp grain crude fat from the field trial at the Oberer Lindenhof, (across harvest years 2018–2020) for the cropping systems (a) 15 cm and 40 kg N/ha, (b) 15 cm and 120 kg N/ha, (c) 45 cm and 40 kg N/ha, and (d) 45 cm and 120 kg N/ha.

Linoleic acid, the omega-6 source of hemp oil, shows a similar behavior. Neither fertilization ($p = 0.7877$), nor row width ($p = 0.7937$) and their interactions produce a statistically significant result regarding the proportion of fatty acid in the plant. This is also the case with crude fat.

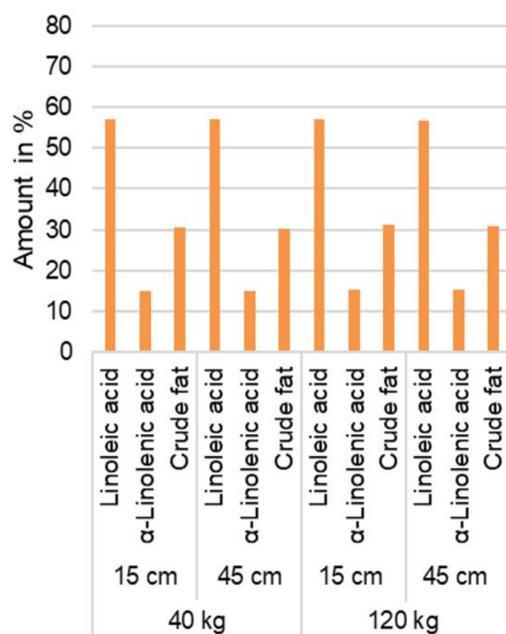


Figure 7. SAS results of the fatty acid concentration in hemp seeds. Results show that the amount of the depicted fatty acids linoleic acid and α -linolenic acid (in % of crude fat) as well as crude fat (in % of total grain dry matter) resemble each other across the different treatments.

3.2.3. Hemp Root Biomass

The fraction of roots of the total collected fresh matter of hemp amounts to an average value of 23.72% (Table 10). The average DM yield lies at 0.86 Mg/ha. Together with a phenological comparison, these values will be compared with literature in the Discussion section.

Table 10. Root biomass share of total biomass (“Biomass fraction”) and DM yield in Mg/ha of hemp roots per plot as well as the average value of both measurements.

Treatment	Biomass Fraction (%)	Root DM Yield (Mg/ha)
15 cm—40 kg N	25.8	1.2
15 cm—120 kg N	20.9	1.5
45 cm—40 kg N	25.8	0.3
45 cm—120 kg N	22.4	0.4
Average	23.7	0.9

3.2.4. Self-Thinning Effect

The self-thinning effect is an important factor to recognize whether, and if so, which external influences during the growth period of hemp negatively affect the biomass yield. The measured values from the year 2021 are shown in Figure 8. The row width, as the single parameter, has a significant influence on the biomass yield in total. The value shown is the calculated percentage difference between the number of plants per m² just before harvest (BD2) and during field emergence (BD1), considered to be at the beginning of the growing season. With a row spacing of 45 cm, an average loss of plants of 45.41% was calculated. Plots with a row spacing of 15 cm had more plants per m² before harvest than at field emergence, resulting in a mean value of −51.83% (the value here is negative because the formula assumes that there are more plants just before harvest than at field emergence). The difference shown here is statistically significant at $p = 0.0003$ with $\alpha = 0.05$ as mentioned in Table 11.

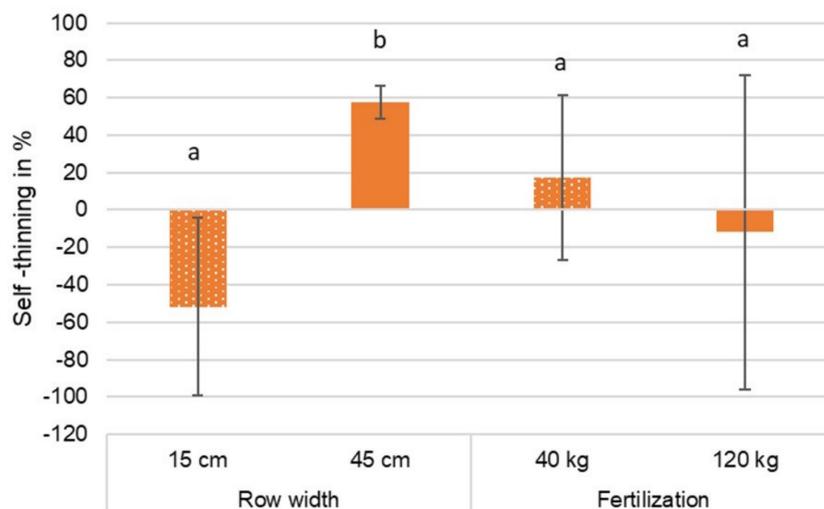


Figure 8. Hemp self-thinning values sorted by row width and fertilization strategy (year 2021). Different letters denote significant differences between the two row widths and fertilization rates, respectively.

The same principle was applied for the fertilizer levels. Here, the mean values of -11.95% with 120 kg N and 17.52% with 40 kg N are produced. With $p = 0.4639$ this difference is not significant, but it appears that with 120 kg N fertilization more plants grew after the first measured value (BD1) (Figure 8).

Using row width \times fertilization, the four treatment strategies of hemp were compared with each other. The results are shown in Table 11.

In this analysis, the result shows five different significance effects. It is noticeable that the only non-significant interaction is the one where both treatment strategies have a row width of 45 cm. For all three analyzed effects (row width, fertilization and row width \times fertilization), high standard deviation values can be observed. It is, therefore, assumed that the measured data have a high dispersion surrounding the mean value. This will be further analyzed in the discussion.

Table 11. SAS results of the interaction row width \times fertilization for self-thinning in hemp. All p -values ($Pr > |t|$) < 0.05 show that there is a statistical significance.

Row Width 1	Fertilization 1	Row Width 2	Fertilization 2	Pr > t
15 cm	120 kg	15 cm	40 kg	0.0313
15 cm	120 kg	45 cm	120 kg	0.0003
15 cm	120 kg	45 cm	40 kg	0.0003
15 cm	40 kg	45 cm	120 kg	0.0085
15 cm	40 kg	45 cm	40 kg	0.0090
45 cm	120 kg	45 cm	40 kg	0.9658

3.2.5. Stand Density of Hemp

Stand density of hemp was measured every four years right before harvest. The measurements might indicate differences in stand density, perhaps caused by row spacing or fertilization. With relation to fertilization, the mean values were 96.19 plants per m^2 , for 120 kg N, and 97.88 plants per m^2 , for 40 kg N (Figure 9). This difference is not statistically significant at $p = 0.7942$, indicating that fertilization has no effect on hemp stand density. As with the fertilization parameter, proc mixed was also used to analyze stand density in relation to row width. The measurements resulted in the following mean values: 153.84 plants per m^2 (at 15 cm) and 40.13 plants per m^2 (at 45 cm) (Figure 9). The difference in these values reached a statistically significant result of $p = 0.0424$ at $\alpha = 0.05$. Thus, there is a significantly higher stand density at row width 45 cm.

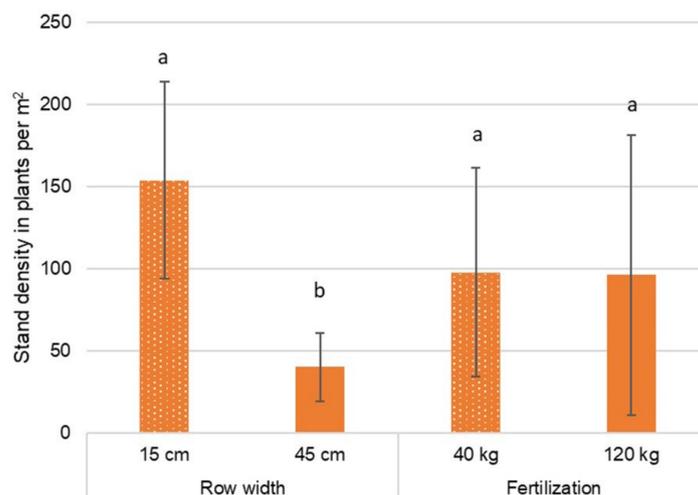


Figure 9. Proc mixed results of hemp stand density, sorted by fertilization and row width strategy separately. Vertical bars indicate the standard deviations of the means. Different letters denote significant differences between the two row widths and fertilization rates, respectively.

The same was calculated for the row width × fertilization effect. Four out of six interactions are statistically significant, as shown in Table 12.

Table 12. SAS results of the interaction row width × fertilization of hemp stand density. All *p*-values ($Pr > |t| < 0.05$) show that there is a statistical significance.

Row Width 1	Fertilization 1	Row Width 2	Fertilization 2	Pr > t
15 cm	120 kg	15 cm	40 kg	0.6984
15 cm	120 kg	45 cm	120 kg	0.0419
15 cm	120 kg	45 cm	40 kg	0.0455
15 cm	40 kg	45 cm	120 kg	0.0443
15 cm	40 kg	45 cm	40 kg	0.0482
45 cm	120 kg	45 cm	40 kg	0.5233

3.2.6. Vegetative Growth Stage

In the experimental year 2021, the developmental status of hemp was determined every week. These observations were made to indicate possible changes in the development of the plants that could be due to the marginal site conditions. The results of these observations are presented below and compared to the developmental process of plants in normal locations. According to Schöberl et al. [44], the vegetative growth stage of hemp focuses on stem and leaf development. The development to the fifth pair of leaves takes a long time but after that there is a period of rapid growth [44]. During this period, intensive development of the stem and internodes takes place. Clarke [53] says that hemp can grow up to 7 cm per day in height at this stage. The number of pairs of leaves that hemp forms ranges from 7 to 12 [44].

- By the time hemp developed the fifth pair of leaves, 40 days, or almost 6 weeks, had passed (31 May 2021–9 July 2021).
- After that, only 2 weeks passed (23 July 2021) until phyllotaxis was observed in half of the plots. The rapid growth after the growth of the fifth leaf pair is hereby confirmed.
- The statement of Clarke [53] that hemp can grow up to 7 cm per day during this period could also be observed in this experiment. In the period between 16 July 2021 and 31 July 2021, hemp in plot 6 grew app. 4.8 cm per day.

Therefore, the vegetative stage described in the literature is in line with the hemp development that took place at Oberer Lindenhof.

3.2.7. Generative Growth Stage

This phase is the beginning of the main growth stage of flowers and seed formation. The beginning of this phase is recognizable by the so-called phyllotaxy, the shift in the leaf position from opposite to alternate [44]. Reaching this point is called the GV point [44] (Table 5). In this phase, the growth cycle of hemp at Oberer Lindenhof is in line with data described in the literature. Phyllotaxis started on 23 July 2021 in half of the hemp plots, as mentioned above, and could be clearly observed (Figure 10a–c).

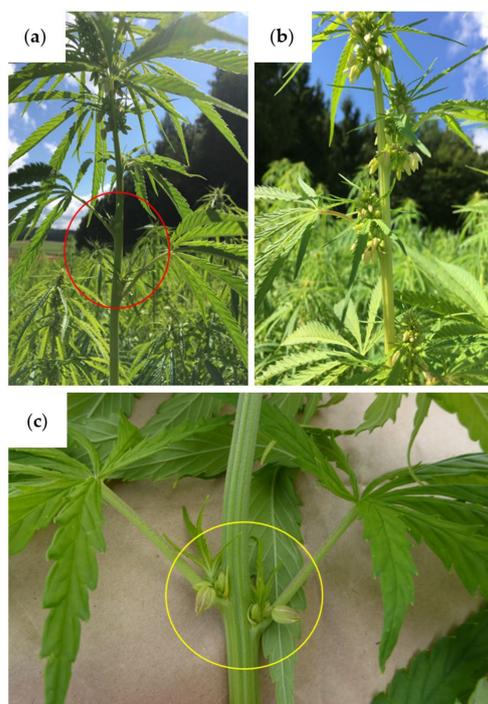


Figure 10. Generative growth stage of hemp, which encompasses phyllotaxy ((a), circled in red) and flower primordia ((c), circled in yellow). (b) shows an already advanced stage within the generative growth stage, characterized by a high amount of flower primordia.

3.2.8. Flowering Stage, Seed Maturity and Senescence

After the beginning of the flower primordia, it takes about 4–6 weeks until it comes to the complete flowering of the hemp plant [44]. In dioecious plants, male flowering occurs first (2100) (staminate flowering) and female flowering occurs about 2 weeks later [44]. The peak of male flowering is the time of technical maturity for high fiber yield [44].

The male flowering of hemp in 2021 occurred within 22 days after the first sighting of phyllotaxis, on 13 August 2021. The almost three weeks in this case represent a shorter time as stated in the literature. The female flowering was observed first on 20 August 2021 and, thus, already took place 7 days after the male flowering. Again, the interval between male and female full flowering is shorter than indicated in the literature.

Additionally, Figure 11a shows a close-up of the female dioecious flower, which clearly visualizes the resin-secreting glandular hairs (trichomes), which are characteristic of the female flower.

About 4–6 weeks after the peak of female flowering (2101), seed maturity occurs [44]. This is the time of technical maturity for seed harvesting [44]. Consistent with the literature, seed maturity (stage 2204) of the female dioecious hemp plant occurred four weeks after peak flowering. Seed maturity was first evident on 23 September 2021 and is shown in Figure 11b. In this end-of-growth phase, desiccation of foliage leaves and stems occurs [44]. In some plants, the senescence of hemp could already be partially observed on 23 September 2021 and is shown in Figure 11c.

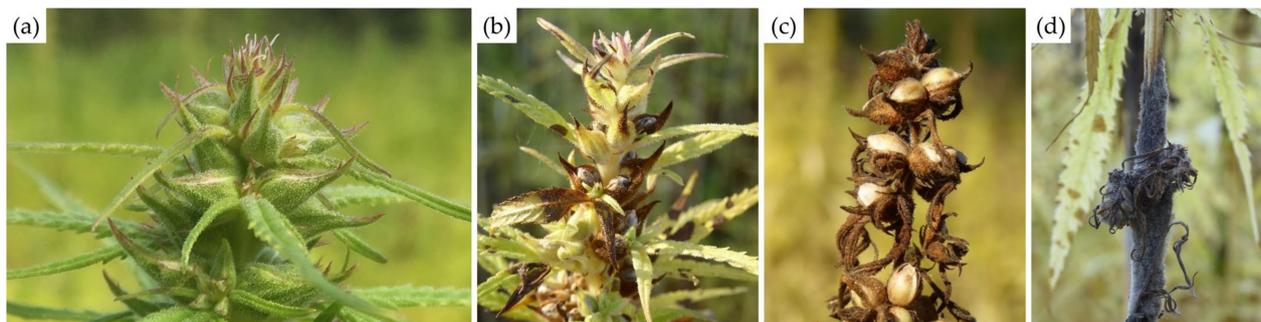


Figure 11. (a) Close-up of a dioecious female hemp plant, which is currently in its flowering stage. This can be identified through the multiple white dots/lines on the seed bracts of the female inflorescence, which are trichomes. (b) Dioecious female hemp plant at seed maturity. Seeds are already observed to be emerging from the seed bracts. (c) Senescence stage of hemp, identified by the wilted foliage leaves and seeds, which are ready to leave the seed bracts. (d) Gray mold found in several plots on 23 September 2021.

3.2.9. Comparing to Monoecious Plants

Although the hemp variety Markant is a dioecious variety, according to one of the breeders at Vandinter Semo B.V., it can always be the case that some monoecious varieties occur. Compared to the dioecious plant, it could be observed in 2021 that monoecious plants sometimes reached senescence faster than dioecious plants. However, in some cases, only the male flower on the monoecious plant has wilted and seed maturation is still taking place.

3.2.10. Diseases

Towards the end of the field trial, gray mold infection was observed on hemp (Figure 11d). Gray mold is caused by the fungus *Botrytis cinerea* [44,54]. In fiber cultivars such as Markant, the fungus attacks the stem of the hemp plant [44,54]. As seen in Figure 11d, gray-black spots on the stems are characteristic of the disease and, as it progresses, cause the plant to break off [44,54].

3.2.11. Height

Height measurements exhibited different growth heights within the different treatment strategies 15 and 45 cm, and 40 and 120 kg N. The two different fertilizer levels, 40 and 120 kg N, indicate no significant difference in height growth of hemp with $p = 0.1790$ at $\alpha = 0.05$. Despite lack of statistical significance, the 120 kg N resulted in higher growth of hemp plants, as shown for the 15 cm row width in Figure 12.

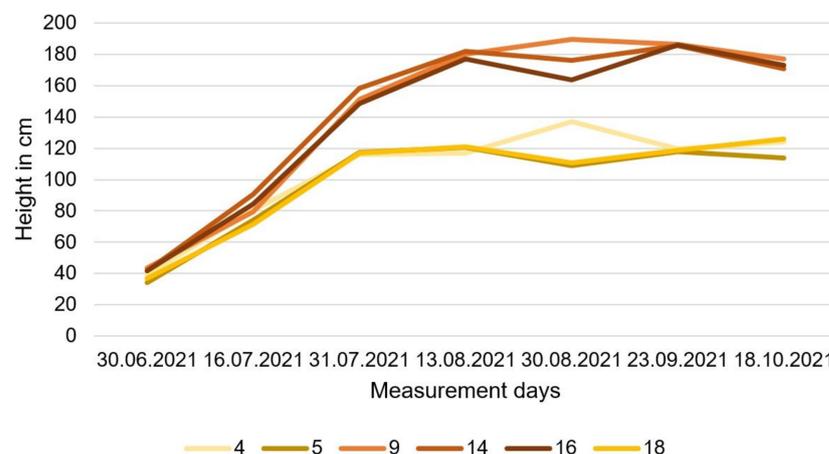


Figure 12. Height measurements of treatments “15 cm, 40 kg N/ha” (plots 4, 5, 18) and “15 cm, 120 kg N/ha” (9, 14, 16) taken regularly at a two-week interval in 2021.

Row spacing 15 and 45 cm, in direct comparison, indicated a statistically significant difference with $p = 0.0392$, at a significance level of $\alpha = 0.05$. Additionally, all treatments were compared with each other and were not grouped by fertilization or row width. The details of the different interaction effects are shown in Table 13.

Table 13. SAS results of the interaction row width \times fertilization for hemp height. All p -values ($\text{Pr} > |t|$) > 0.05 show that there is no statistical significance.

Row Width 1	Fertilization 1	Row Width 2	Fertilization 2	Pr > t
15	120	15	40	0.1476
15	120	45	120	0.0803
15	120	45	40	0.4103
15	40	45	120	0.0507
15	40	45	40	0.0370
45	120	45	40	0.2965

3.2.12. Wildlife

Wildlife was observed throughout the experimental phase in 2021. As already pointed out, hemp is an ecologically valuable plant, as its late flowering provides an important pollen pool for bees. In August 2021, high numbers of bees were observed and photographed in the hemp plots. The bee population was observed visually only, indicating a high abundance of the animals. This could also be perceived auditorily by a continuous buzzing of bees. The bees, which can also be seen in the pictures in Figure 13, were determined to be *Apis mellifera*, the European honeybee. The high component of bees observed in 2021 suggests that hemp, in addition to being a valuable industrial crop that can grow in numerous conditions, can also provide ecological value. As it is essential to sustain pollinators and to provide a healthy and functioning ecosystem, the ecological value of an industrial plant is important to condition its continued cultivation [55].



Figure 13. Wild bees carrying their pollen sac during hemp flowering in August 2021.

In addition to bees, birds were also increasingly observed in the hemp fields (Figure 14). The experimental field at Oberer Lindenhof is located directly next to a forest and may be one of the reasons for a high bird occurrence.



Figure 14. Common chaffinch (*Fringilla coelebs*) observed in one of the hemp plots at Oberer Lindenhof in 2021 (adapted from Burland and von Cossel [26]).

3.3. Quantitative Analysis

3.3.1. Stem DM Yield Results

With respect to fertilization, analysis in SAS with proc mixed shows that fertilizer applications of 40 kg and 120 kg N result in mean stem yields of 5.11 Mg/ha and 6.08 Mg/ha, respectively. Thus, the higher stem yield is detected here with a fertilizer application of 120 kg N (Figure 15). However, the difference with fertilization with 40 kg N is not statistically significant with $p = 0.3080$ at $\alpha = 0.05$. The test determined the following mean values: 5.78 Mg/ha for 15 cm and 3.62 Mg/ha for 45 cm (Figure 15). At $p = 0.0908$, this difference is statistically insignificant. However, despite insignificance, it can be seen that the row width 15 cm tends leading to a higher stem yield in Mg/ha (Figure 15).

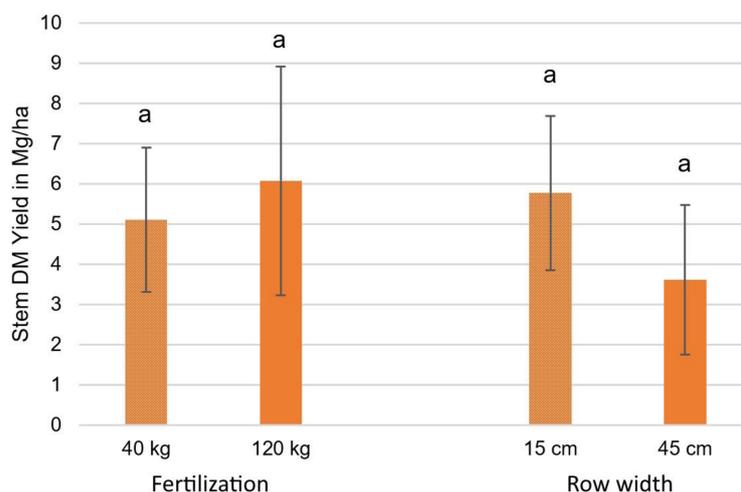


Figure 15. Proc mixed results of stem DM yield of hemp, categorized by fertilization and row width strategy separately. Vertical bars indicate the standard deviations of the means. Same letters denote no statistically significant difference between the means.

3.3.2. Grain DM Yield Results

The average grain DM yield in the last four years was 1.59 Mg/ha for 15 cm row spacing and 1.38 Mg/ha for 45 cm row spacing (Figure 16). The same was performed for the fertilization parameter, but again the different mean values at 40 kg N (1.34 Mg/ha) and 120 kg N (1.62 Mg/ha) showed no significance with $p = 0.2194$ (Figure 16).

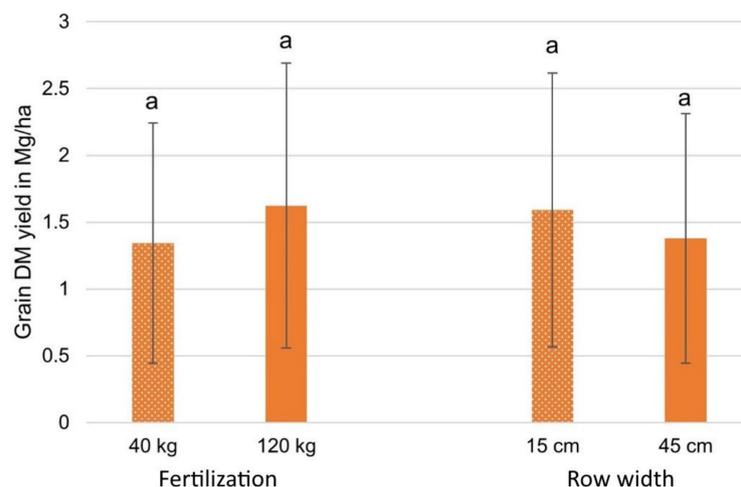


Figure 16. Proc mixed results of grain yield hemp, sorted by fertilization and row width strategy separately. Same letters denote no statistically significant difference between the means.

3.3.3. Reference Crop Maize

The DM yield of silage maize accounted for 19.2 ± 0.5 Mg/ha (2020) and 17.8 ± 2.8 Mg/ha (2021), respectively.

4. Discussion

4.1. Soil Conditions and Plant Phenological Development

4.1.1. Soil

Various soil measurements were conducted at Oberer Lindenhof, and the results were analyzed using the Soil Texture Triangle [56]. The soil was classified as silty clay, with an average composition of 43.7% clay, 12.2% sand, and 44.1% silt.

The clay and silt contents were higher than expected. Amaducci et al. [8] reported that sandy loam (60% sand, 30% silt, 10% clay) and clay loam (20% sand, 60% silt, 30% clay) are optimal for hemp cultivation, whereas heavy clay soils, such as those at Oberer Lindenhof, are considered unsuitable. Similarly, von Cossel et al. [43] identified high clay and sand content as major constraints for crop production, primarily due to excessive water retention (which becomes critical at clay contents > 50%) and poor air permeability. Reduced air permeability can restrict oxygen availability to plant roots and soil microbiota, potentially causing plant hypoxia, which leads to lateral root growth as an adaptive response [43,57]. Additionally, the shrink-swell behavior and low porosity of clay soil can result in root damage due to water accumulation on the soil surface following rainfall events [43]. Consequently, the findings of this study may not be directly applicable to other sites with shallow soils unless they also exhibit high clay content.

Clay can also influence nitrogen dynamics. Ruchkina et al. [58] reported that clay-rich soils can fix nitrogen, leading to increased nutrient availability [59,60]. Additionally, the elevated N_{\min} values observed in 2020 and 2021 may be attributed to organic matter mineralization following the conversion of former grassland. This process likely contributed to the high pre-sowing N_{\min} levels (60–70 kg N/ha in May; Table 8).

A direct comparison of quantitative and qualitative factors between low-input and high-input fertilization was initially planned but could not be conducted due to the high N_{\min} contents. As a result, instead of the intended 40 kg N/ha, actual nitrogen inputs reached approximately 100 kg N/ha, while the 120 kg N/ha treatment resulted in an estimated 180 kg N/ha. Given the typical fertilization ranges of 80–100 kg N/ha for grain hemp [61] and 100–160 kg N/ha for fiber hemp [62], the intended low-input condition was not achieved. Consequently, the 40 kg N/ha treatment cannot be classified as a true

low-input variant, which may explain why stem and grain yields did not differ significantly between the fertilization treatments, contrary to previous literature.

While the pH remained within the recommended range of 6.0–7.5 [8], the shallow soil depth (~15 cm) posed an additional constraint. Von Cossel et al. [43] classify soil depths less than 30 cm as marginal for crop growth. However, it remains unclear whether the observed results were primarily due to the shallow soil profile or the high clay content, as the latter also imposed limitations, while the elevated N_{\min} levels may have mitigated some of these constraints.

4.1.2. Stone Content

As can be seen in Table 14, the soil at Oberer Lindenhof has a stone content of 12.3% on average. There is little literature on the influence of stony soil on the growth of the hemp, so no direct comparison of the observed effects with other studies can be made.

Table 14. Stone content in the topsoil of the field trial at Oberer Lindenhof. Water in ml (with stones), water in ml (without stones), volume of digging hole in m^3 , and volume of stones in m^3 are the values with which the percentage of the stones in the soil were calculated. In the last row, the average stone content of the soil is displayed.

Treatment	Percentage of Stones in Topsoil Sample (%)	Standard Deviation (%)
15 cm—40 kg N/ha	13.7	2.7
15 cm—120 kg N/ha	10.4	2.5
45 cm—40 kg N/ha	13.4	1.5
45 cm—120 kg N/ha	16.9	3.5
Mean value	13.6	

Nevertheless, a stone content of >10% is classified as sub-severe by Elbersen et al. [63], and it is clear that stone content together with shallow soil has an influence on plant growth in general, especially on root development [28,30,63]. High stone content limits the growth area for roots, the storage area for nutrients and water, affects the germination of seeds and creates a more difficult working situation for agricultural machinery [28,63]. This impact together with the aspects mentioned above is considered negative by Elbersen et al. [63].

4.1.3. Stem Width

In line with previous studies, the results of this study confirm that plant population density is a key determinant of hemp stem width. Amaducci et al. [64] report that fiber cell diameter decreases with increasing plant population, attributing this effect to intensified interplant competition [65]. In particular, competition for light results in the development of thinner stems [66].

In the MAGIC trial 2021, hemp grown in 45 cm row width plots produced significantly thicker stems, consistent with existing literature, as the lower stand density reduced interplant competition.

For the textile industry, thinner stalks are advantageous, as they enhance fiber quality [64]. Consequently, hemp cultivated for textile applications is typically harvested during flowering, when the primary fiber content is highest and lignification remains low [67]. The findings of this study suggest that hemp grown under narrow row spacing (15 cm), which results in higher stand density, is well-suited for fiber production.

However, environmental factors such as high winds and heavy rainfall, which occurred frequently from 2019 to 2021, as well as bird activity in the plots, caused greater damage in the narrow-row plots. The thinner stems were less resilient to mechanical stress [68].

From a climate resilience perspective, particularly in light of increasing extreme weather events, wider stems may be preferable to ensure stable biomass production [10,69,70].

4.1.4. Fatty Acid Content

Figure 10 presents the results of the fatty acid composition analysis of hemp. To assess whether the marginal site conditions at Oberer Lindenhof influenced seed quality, these results were compared with findings from the literature (Table 15).

Table 15. Fatty acid composition of hemp compared with published data.

Fatty Acids	Components (in % <i>w/w</i>) as Reported by [71,72]	Components (in % <i>w/w</i>) as Reported by [73]	Components (in % <i>w/w</i>) of This Study (Average Across All Treatments)
Linoleic acid (18:2 ω 6)	50–70	52–62	57.0
α -Linolenic acid (18:3 ω 3)	15–25	12–23	15.1
Palmitic acid (16:0)	6–9	5–7	6.3
Eicosanoic acid (20:0)	0.79–0.81	0.39–0.79	1.9
Eicosenoic acid (20:1)	0.39–0.41	0.51	0.4

When comparing the results with previous studies (Table 16), it is evident that eicosanoic acid levels were higher in hemp than in reported values, whereas all other fatty acid contents were within a similar range. Notably, the published studies referenced here rely on data from the genotype Fedora-19, a French hemp variety, whereas no comparable data were available for Markant. This suggests that the elevated eicosanoic acid content observed in hemp may be attributed to genotypic differences.

Contrary to Tedeschi et al. [74], nitrogen fertilization with 120 kg N/ha did not significantly alter the fatty acid composition compared to 40 kg N/ha. A possible explanation is that fertilization at both levels was affected by the high clay content in the soil. While the intended contrast between low-input (40 kg N/ha) and high-input (120 kg N/ha) fertilization remained, both fertilization rates were substantially high. As a result, a clear differentiation between low- and high-input conditions, such as those in Tedeschi et al. [74], could not be observed.

In contrast, the findings regarding row width align with previous research, showing no statistically significant differences in the fatty acid composition between 15 cm and 45 cm row spacing. Stafecka et al. [75] similarly conclude that plant population has a negligible effect on fatty acid composition. This is particularly relevant because hemp stand density is adjusted based on its intended application—grain or fiber production [75]. For grain hemp, the optimal seeding rate is 30 kg/ha, or approximately 100–150 plants per m² [76]. If stand density had significantly influenced seed quality, adjustments to seeding rates would be necessary based on the desired end use.

Table 16. Measurements of belowground dry biomass yield and root biomass fraction of hemp compared to the measurements of the research performed by Amaducci et al. [77]. Measurements of Amaducci et al. [77] were obtained for two years: 2004 and 2005.

Year of the Study	Belowground Dry Biomass Yield Hemp in Mg/ha	Root Biomass Fraction in %
2021 (this study)	0.86	23.72
2004	3.21 [77]	18.24 (calculated with data of [77])
2005	2.41 [77]	18.54 (calculated with data of [77])

The findings of this study indicate that neither the marginal site conditions nor the low-input fertilization approach affected hemp seed quality. However, further research is crucial, as seed quality plays a key role in agriculture and food security [74]. Tedeschi et al. [74] highlight that temperature strongly influences the balance between monounsaturated oleic acid (not assessed in this study) and linoleic acid during seed development. Given the implications of climate change, continuous monitoring of these factors is essential to maintain the quality and multifunctionality of fiber hemp.

4.1.5. Underground Biomass and Root Morphology

The hemp roots of this study developed significantly fewer fine roots compared with Wagner [78], and they adopt an L-shaped growth pattern, as was also described by Amaducci et al. [8] and Desanlis et al. [79]. Additionally, hemp produced fewer roots overall, particularly fewer horizontally growing roots than expected. These differences can be attributed to the shallow, stony soil at Oberer Lindenhof.

According to Amaducci et al. [77], when unrestricted, hemp roots can extend up to 200 cm in search of water sources. However, at Oberer Lindenhof, root growth was constrained by a compaction layer, a parent rock layer that prevented optimal root development. In shallow soils with a compaction layer, hemp's taproot spreads horizontally [68]. However, the high stone content in the soil at Oberer Lindenhof appears to have further limited horizontal root expansion, preventing hemp from spreading as reported in the literature [80].

In addition, differences were observed in the belowground dry biomass yield and the root biomass fraction compared to published data. Table 16 compares the results of this study with those from Amaducci et al. [77]. As expected, the belowground dry biomass yield of hemp was significantly lower, likely due to the marginal site conditions. As discussed earlier, root growth is limited in shallow soils [81], preventing biomass accumulation comparable to that in deep, fertile soils.

Interestingly, the root biomass fraction (i.e., the proportion of root biomass relative to total plant biomass) was higher than in Amaducci et al. [77]. This can be explained by the restricted root growth at Oberer Lindenhof, which likely hindered nutrient and water uptake [8]. As a result, the plants produced less aboveground biomass, increasing the relative proportion of root biomass. Furthermore, Scordia et al. [68] suggest that wider row spacing (45 cm) may enhance root development by reducing intraspecific competition.

4.1.6. Self-Thinning and Stand Density

The results of self-thinning and stand density in hemp show that the wider row width (45 cm), i.e., the wider plant cultivation resulted in a higher occurrence of self-thinning and the 15 cm row width, thus, showed a higher stand density before harvest. The denser plant cultivation with 15 cm row width even had more plants immediately before harvest as in the first measurement shortly after sowing. These conclusions are contrary to the literature, which states that higher density of hemp due to interplant competition results in higher plant loss [45,82,83]. This is also confirmed by Amaducci et al. [66] (p. 33), who describes the following in his research: “[...] *plant loss* [...] *was negligible at low density* [...], *while at high density* [...] *50% and 60% of the initial stand was lost, respectively.*” The reason for this is not known and could not be answered by a literature search. However, a theory can be proposed based on data from Amaducci et al. [66]. They describe that hemp plants show different growth characters in the early growth phases depending on the stand density. High density crops experience high light competition and put most of their energy into growing the stem in the early stages to reach the light [66]. Low density crops, on the other hand, do not have this light competition and put their energy into leaf growth, resulting in

canopy closure [66]. Thus, low density crops do not grow as much in height as high-density crops [66] in the initial phase (this is important to note, as this changes towards the end of the growth phase) [84] and, thus, do not gain the same stem biomass, which could make them more unstable. The thunderstorm on 28 June 2021, where there was a rain rate of 27.5 mm in one hour, may have had an impact on hemp plant growth, especially on the more unstable hemp plants, which could have led to a higher rate of self-thinning in the longer term. Figure 17 shows that plots 7, 15, and 20 (45 cm row width and 40 kg N fertilization) initially remain at the same level in terms of height as plots 4, 5, and 18 (15 cm row width and 40 kg N fertilization). This changes from 31 July 2021 onwards, with the 45 cm row width plots growing higher.

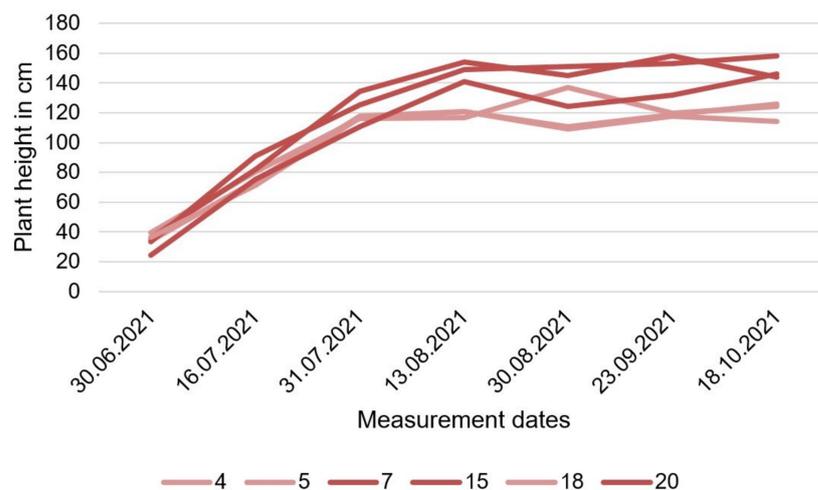


Figure 17. Plant height in cm for plots 7, 15, and 20 (45 cm–40 kg N) and plots 4, 5, and 18 (15 cm–40 kg N) over the course of measurements days in 2021.

However, a clear initial deviation in height growth, as described in the literature, is not observed.

The 15 cm row width resulted in a higher stand density and a lower stem width, which is a promising result for the textile industry. Amaducci et al. [66] describes that for textile application of hemp, a stand density of 100 plants per m^2 is advised (or even more). The reason for this is that higher stand density results in thinner stems, which is optimal for the application of hemp in the textile industry. Hemp achieved a stand density of nearly 150 plants per m^2 at a row width of 15 cm, illustrating that the 15 cm row width and especially the marginal site conditions of shallow and stony soil meet the requirements of hemp in the textile industry.

In terms of the effect of the fertilization variants to self-thinning or stand density, no significance is shown between the two variants. In their research, van der Werf et al. [85] describe that hemp growth is indirectly influenced by the amount of nitrogen, as more self-thinning occurred at 200 kg N than at 80 kg N. The fact that this was not the case with hemp could be due to the already mentioned high soil N_{min} at Oberer Lindenhof. However, what was noticed in the evaluation of the results were high values of standard deviation in the fertilizer readings. This shows that there was a lot of variation in the measured values, which could be appointed to plant damage through wildlife interaction.

For the row width \times fertilization interaction, there was a significant difference between treatment variants 1 (15 cm–40 kg N) and 2 (15 cm–120 kg N). The comparison of the two fertilization variants alone did not result in statistical significance. Thus, it can be concluded that with a denser plant quantity, the 120 kg N in hemp leads to an even higher stand density. Namely, the estimate of the self-thinning value for treatment 2 was 81.81%, while the value for treatment 2 was 21.85%. It is suggested that the higher fertilization with

120 kg N in hemp, which suffered from interplant competition due to high stand density, calmed the competition for nutrients, and, thus, more plants survived.

4.1.7. Plant Appraisal

The results indicate that the vegetative and generative growth stages of hemp align with established literature. However, the flowering stage in hemp occurred earlier than described by Amaducci et al. [8], suggesting that hemp may have a distinct phenological development. According to Amaducci et al. [8], the flowering stage is crucial for the formation of stems, grains, and inflorescences and is influenced by factors such as nitrogen fertilization, row spacing, and stand density [84,86–88]. The influence of low-input conditions, row width, and marginal site conditions on the timing of the flowering stage was not fully discernible in this study, but this aspect warrants further investigation. Accurately identifying the onset of flowering is important for decision support systems in hemp production, as this timing impacts the yield of both grains and stalks [87]. Hemp genotypes that flower earlier typically exhibit reduced height growth and stem yield. Therefore, the flowering stage significantly affects the overall grain and stem yield [89]. Further research is recommended to better understand why the flowering stage in hemp occurred earlier than described in the literature.

The timing of seed maturation in hemp was consistent with the literature. However, senescence occurred earlier in some plants than others, which could be attributed to the gray mold disease (Figure 11d).

4.1.8. Height

According to the literature, hemp typically shows increased height with higher nitrogen supply [90,91]. Although the study by Papastylianou et al. [92] did not find a significant effect, a trend of greater plant height with increased nitrogen is still evident. The genotype of the hemp plant is believed to exert a stronger influence on plant height [92]. At Oberer Lindenhof, low-input fertilization (40 kg N) resulted in shorter plants compared to the control treatment (120 kg N), although the difference was not statistically significant. A comparison with data from other studies is shown in Table 17.

Table 17. Measurements of hemp plant height in cm compared to previous studies by [92,93].

Source	Plant Height in cm
Results (40 kg N)	~167.75
Results (120 kg N)	~187.09
Results (15 cm)	~161.97
Results (45 cm)	~192.87
Reported by [92] (0 kg N)	166
Reported by [92] (240 kg N)	176
Reported by [93]	300–350

Hemp data deviate from literature, except for the data from 2021. Upon analyzing only the 2021 measurements, a significant difference was observed between the two fertilizer treatments. This is visually supported by a photograph in Figure 18.

Why is the 2021 comparison significant, while the comparison across all years is not? Kakabouki et al. [94] note that plant height is significantly influenced by fertilization, variety, and location. Hemp has been grown at Oberer Lindenhof since 2018, though in different locations on the site, which may have resulted in varying growing conditions across years. Proximity to the forest could have provided plant protection during thunderstorms, and higher bird predation may have occurred near the forest. Therefore, to draw a conclusive statement on the effects of low-input conditions on plant height, further studies with

consistent growing conditions over a longer period are recommended, particularly to maintain a true low-input fertilization regime at 40 kg N.

Regarding row width and its effect on plant height, varying opinions exist. Van der Werf et al. [85] report a decrease in height with increasing row width, but this was not observed in hemp. Typically, narrower row widths (such as 15 cm) lead to increased plant height and biomass accumulation, while also limiting radial expansion due to interplant competition [95]. However, in Oberer Lindenhof in 2021, some stems exhibited growth patterns shown in Figure 19, likely due to breakage during severe weather events in the early growth phase, followed by recovery. These broken stems were included in the height measurements, which may explain why hemp at 15 cm row width did not achieve the expected height. Thinner stems, typical of narrower row widths, may be more susceptible to weather-related damage, potentially hindering height growth.



Figure 18. Hemp plot fertilized with 120 kg N (left) vs. plot fertilized with low-input conditions (right) in 2021. Significant height differences are visible, which are supported by SAS analysis when considering only the 2021 data.



Figure 19. Bent hemp stems observed at Oberer Lindenhof in 2021.

Based on the results, wider row widths (45 cm) and higher fertilization rates (120 kg N) lead to higher plants. However, 45 cm row width also resulted in significantly thicker stems (see section on stem width). Therefore, a row width of 15 cm is recommended for textile purposes, because it results in shorter plants, producing finer stems suitable for the textile industry. However, it is not advisable to promote plant height

for fine stalks, as they would be more vulnerable to weather events, which are expected to increase with climate change [10,69,70]. Furthermore, height is not the key determinant for textile use of hemp; rather, fiber strength, refinability, and fineness are more crucial [96].

Concerning marginal site conditions, Kakabouki et al. [94] found that root density correlates positively with plant height. At Oberer Lindenhof, root density cannot be assured due to the stony, shallow soil. Nevertheless, this did not seem to affect hemp, as its height aligns closely with the literature, indicating that hemp can thrive in marginal conditions such as shallow and stony soil, at least regarding plant height.

4.1.9. Weed Competition

In the context of weed competition, significant weed presence was observed in the camelina and calendula plots, which, as mentioned in 2.3, were also included in the field trials but not addressed further in this study. As shown in Figure A1, the camelina and calendula plots were heavily infested with weeds. By contrast, the hemp fields showed no such weed infestation, although no weed control or herbicide measures were carried out. This ability of hemp to grow without substantial interference from weeds suggests that it could be a viable option for environments where weed management is challenging, e.g., along buffer strips close to water bodies. Furthermore, no noticeable differences in weed presence were observed between the different row widths or fertilization levels, suggesting that hemp's resistance to weeds is independent of this cultivation factor.

4.2. Biomass Yield

4.2.1. Stem DM Yield

Table 18 shows a comparison of the data measured in this study with data from the literature. The direct comparison with measurements from Markant in other studies shows that hemp yields are similar to those from France and Italy, while stem yields from the Czech Republic and Latvia are higher (Table 17). The average hemp stem DM yield of 7.3 Mg/ha in Europe in 2010 [97] is similar to the results of this study.

Table 18. Measurements of stem DM yield of hemp compared to the measurements from the research performed by [89,97].

Source	Stem DM Yield in Mg/ha
Results (40 kg N)	5.1
Results (120 kg N)	6.1
Reported by [89] in the Czech Republic	10.9
Reported by [89] in France	7.0
Reported by [89] in Italy	4.4
Reported by [89] in Latvia	9.8
Reported by [97]	7.3

The results of this study suggest that neither fertilization nor row width had a significant effect on stem biomass. During the literature search, it was evident that there is no consensus on this issue. In contrast to the results of this study, three research teams reported positive effects of nitrogen fertilization on hemp stem yield [83,85,92]. Amaducci et al. [98] stated that “each additional kg of nitrogen supplied via fertilization increased stem dry matter production by 20 kg” (as cited by Amaducci et al. [98]). However, Papastylianou et al. [92] also observed that a significant response in stem biomass in terms of nitrogen fertilization only occurs when soil nutrients available to plants are low [83,92,99]. Prade et al. [99] conducted an experiment in Sweden with humus-rich soil and concluded that fertilization up to as high as 200 kg N per ha had no effect on yield. This discrepancy could be attributed to $N_{critical}$ levels. As described

in earlier sections, soil N_{\min} levels at Oberer Lindenhof were higher than intended, which may explain why N fertilization did not result in significant differences in stem yield.

The results regarding stem DM yield in relation to row width are consistent with the literature. Studies report that stand density has little effect on stem yield [83,98]. This is because stem yield tends to stabilize regardless of row width. Low stand density can delay plant canopy development [100] and increase weed occurrence [52], both of which result in yield reduction [52,100]. At high stand density, more and taller stems are present in the plant population, but more self-thinning occurs due to interplant competition [85,101], as described earlier in this study. In this case, the thinning effect was higher at the wider row width, which explains why the 15 cm row width achieved higher, though non-significant, stem yields. This finding supports the literature that suggests row width has no substantial impact on stem DM yield.

Despite marginal site conditions, hemp appears to achieve similar stem DM yields to those reported in the literature for fertile soils. As shown in Table 18, stem DM yields are even higher than those reported for Italy by Tang et al. [89]. However, stem DM yields from the Czech Republic and Latvia were higher. In addition to N fertilization, row width, and marginal site conditions, another factor that could have influenced stem DM yield is the presence of the plant disease gray mold. As shown in Figure 11d, gray mold can cause plant stems to break off or reduce biomass quality, as reported by Schöberl et al. [76]. Nitrogen fertilization has been shown to enhance biocontrol effectiveness against *Botrytis cinerea* in tomatoes [102], and it can also influence spore occurrence of *B. cinerea* [103].

In conclusion, hemp achieved acceptable stem DM yields in this study despite growing under marginal site conditions. However, this is likely due to the higher-than-intended soil N_{\min} , which did not adhere to the low-input conditions originally envisioned. Thus, the true potential for hemp growth on shallow, stony soils with low nitrogen inputs remains unclear. What is certain is that N levels in the soil should not be treated as a benchmark for future cultivation, as excessive soil N_{\min} is undesirable due to its potential negative environmental impacts [100,104,105].

4.2.2. Grain Yield

Within literature, there is no unified view on the effects of N fertilization on the grain yield of hemp. Some say that grain yield increases with increasing N fertilization [90,91,106,107], others discovered through their experiments that grain yield is very little affected by N [92,106–108]. The results of this study rather support the latter statement, because N fertilization had no significant effect on hemp grain yield. In principle, Tang et al. [100] describe that determining grain yield per plot is a challenging task due to bird predation. A similar observation was made in this study. Many birds, including the common chaffinch (as seen in Figure 14) were observed in the hemp plots. It is, therefore, reasonable to assume that the grain yield would have been different if the bird predation described had not occurred.

Regarding row spacing, the results of this study are also in line with the literature, which states that stand density has no significant effect on grain yield [100,105]. Legros et al. [105] describe that a seeding rate of up to 40 kg/ha (which is 200 plants per m^2), had no effect. For hemp in this study, the seeding rate was 20 kg/ha. The reason that row spacing has no effect is that grain yield per plant increases with lower stand density, because with lower stand density the inflorescence length increases and also more branches are formed, which then produce grains [78]. So, a high stand density generally has more plants, and a low stand density has fewer plants but more yield per plant, which then ultimately balances out.

A look at the Markant measurements in the study of Tang et al. [89] (Table 19) shows that they are similar to the hemp values. The study does not indicate that the growing

soils are marginal. Thus, hemp grown on shallow, stony soil can keep up with Markant grown on fertile soil in terms of grain yield. However, Tang et al. [89] also states in his study that “special attention should be paid when choosing MAR for seed production because its seed yield was low despite its early flowering” (as cited in Tang et al. [89]). This is also reflected in Table 19, where the comparison of the Markant measured values with the average grain yield of 11 other monoecious hemp varieties can be seen [109]. A grain yield of 0.25 Mg/ha is very low compared to Markant values. In fact, according to Tang et al. [89], Markant as an early flowering cultivar should produce high grain yields (especially compared to late flowering cultivars) [89]; however, the proportion of all-male plants, the occurrence of which is genetically but also environmentally controlled, can reduce the grain yield [110,111]. In the context of this study, an investigation regarding the number of male, female, and hermaphrodite hemp plants was completed; however, the results were considered unusable because the competence to determine the plants according to their gender was not yet established enough at the time of the measurement.

Table 19. Measurements of grain yield of hemp compared to the measurements of the research performed by [89,109].

Source	Grain Yield in Mg/ha
Results (40 kg N)	1.35
Results (120 kg N)	1.62
Results (15 cm)	1.59
Results (45 cm)	1.38
Reported by [89] in the Czech Republic	1.50
Reported by [89] in France	0.50
Reported by [89] in Italy	1.10
Reported by [89] in Latvia	1.40
Reported by [109]	0.25

Further reasons for the low grain yield of hemp compared to the yield reported by Höppner and Menge-Hartmann [109] (Table 19) could be, firstly, that the disease gray mold had an influence. Gray mold could be observed at Oberer Lindenhof (Figure 11d). The effects of the plant disease included broken stems. Without a completed stem growth, grains cannot form either, which is why gray mold is one of the limiting factors of grain yield at Oberer Lindenhof. With respect to the research question of whether marginal site conditions affect grain yield, reference is made to a statement by [88] who asserts that plants can only take up the nitrogen supplied to them if they have developed a sufficiently good root system. As explained before, the roots of hemp had to adapt to site conditions, which created a growth restriction in the vertical as well as in the horizontal.

4.2.3. Maize

The data presented in Table 20 show that the maize production at Oberer Lindenhof is higher than the silage maize production in Baden-Württemberg and in Germany as a total. The reason for this could be the overfertilization due to the high clay and silt content at Oberer Lindenhof. For maize, it is estimated that a nitrogen fertilization of 180 kg N/ha was present in 2021. The German Maize Committee calculates a N fertilization requirement of 126 kg N/ha for German silage maize [112]. Therefore, the fertilization at Oberer Lindenhof was much higher. Maize is generally considered to be a crop that requires a lot of fertilizer [113], which often leads to nitrate leaching when maize is grown on its own [114,115]. In this study, maize was used as a reference crop. A great deal of data already exists on maize, as it is the most important energy and forage crop [116]. Therefore, it was intended that the effects of the marginal conditions at Oberer Lindenhof

could be analyzed in more detail. The comparison of the data shows that this was achieved, because due to the high clay content there was more nitrogen available in the soil, which resulted in higher dry matter yields (Table 20). However, it is also evident that the shallow, stony soil did not severely affect the growth of maize, at least under the addition of sufficient nitrogen.

Table 20. The DM yield of stem and leaves of hemp compared to the dry matter silage maize yield in Baden-Württemberg and in Germany in general. Data are taken off the website of the German Maize Committee [117].

Year	DM Yield Stem and Leaves of Maize in Mg/ha	Dry Matter Silage Maize Yields (Incl. Biogas Use) in Mg/ha in Baden-Württemberg	Dry Matter Silage Maize Yields (Incl. Biogas Use) in Mg/ha (Total Germany)
2017	-	16.996	16.611
2018	-	15.323	12.352
2019	-	16.695	13.65
2020	19.189	15.719	14.837
2021	17.774	16.650	16.531

4.3. Outlook and Relevance of the Results of This Study

Since the clay and silt content at Oberer Lindenhof was very high, the question arises to what extent the results are relevant for other sites with shallow soils. Research shows that high clay content together with shallow soil has a negative effect on growth conditions [28]. Thus, the high clay content at Oberer Lindenhof cannot be overlooked. Since high clay content can lead to water retention in the soil, the results of this study could be partially relevant to soils with limited soil drainage and excess soil moisture. The conditions of these types of soils usually result in limited oxygen supply to the plants grown and their roots, which has a significant effect on nutrient uptake [118]. Poor air permeability also occurs with high clay content. In addition, soil compaction occurs in soils with limited soil drainage and excess soil moisture, which impairs root development [119]. Here, too, parallels can be drawn with the results of Oberer Lindenhof, where roots could not develop optimally due to the low topsoil depth and the high stone content in the soil. In addition, a high clay content, when the soil dries, also leads to compaction around the plant [28]. Thus, it can be said that the results of this study may be partially relevant for soils with limited soil drainage and excess soil moisture. Regarding other shallow soils, however, no relevance is seen here.

5. Conclusions

This study explored the influence of marginal site factors and low-input conditions on the growth of industrial hemp, aiming to determine its potential as an industrial crop on specific types of marginal land within the European Bioeconomy. The four-year research conducted as part of the EU Horizon 2020 Project MAGIC found that hemp is surprisingly well suited for cultivation on marginal arable land characterized by shallow, stony soil with high clay content. However, the fertilization effect was masked by high soil nitrogen mineralization. However, it was possible to evaluate the impact of different row width, whereas the commonly used narrow row width (15 cm) performed well despite the adverse rooting conditions. It resulted in finer stems, reduced self-thinning, and significantly smaller plants compared to wider row spacing. Therefore, a 15 cm row width is recommended for comparable site characteristics. As synergistic effects of the soil conditions in this study can be assumed, the results are not applicable to shallow soils in general. Nevertheless, this study provides insights into the growth of hemp on shallow, stony soils with high clay and silt content, and it highlights the adaptability of industrial hemp.

Author Contributions: Conceptualization, B.E.G. and M.v.C.; Data curation, B.E.G., T.T. and K.S.; Formal analysis, B.E.G., J.K., T.T., K.S. and M.v.C.; Funding acquisition, M.v.C.; Investigation, B.E.G., J.K., T.T. and K.S.; Methodology, B.E.G., J.K., T.T., K.S. and M.v.C.; Project administration, M.v.C.; Resources, B.E.G. and M.v.C.; Software, T.T.; Supervision, M.v.C.; Validation, B.E.G., G.K., T.T., K.S. and M.v.C.; Visualization, B.E.G. and M.v.C.; Writing—original draft, B.E.G.; Writing—review and editing, B.E.G., G.K., K.S. and M.v.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research has received funding from the European Union’s Horizon 2020 research and innovation programme under the grant agreement No. 727698 (MAGIC: Marginal lands for Growing Industrial Crops: Turning a burden into an opportunity).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank Iris Lewandowski for making this study possible. Special thanks go to the technical staff at the Oberer Lindenhof. The authors also thank Paola Varela Perez for her support during the harvest of hemp.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BBCH	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie
DM	Dry matter
GV point	Change in phyllotaxis on the main stem from opposite to alternate
N _{min}	Amount of mineralized nitrogen
MAGIC	Marginal lands for growing industrial crops: Turning a burden into an opportunity
MAR	Hemp variety “Markant”
PUFA	Polyunsaturated fatty acids

Appendix A

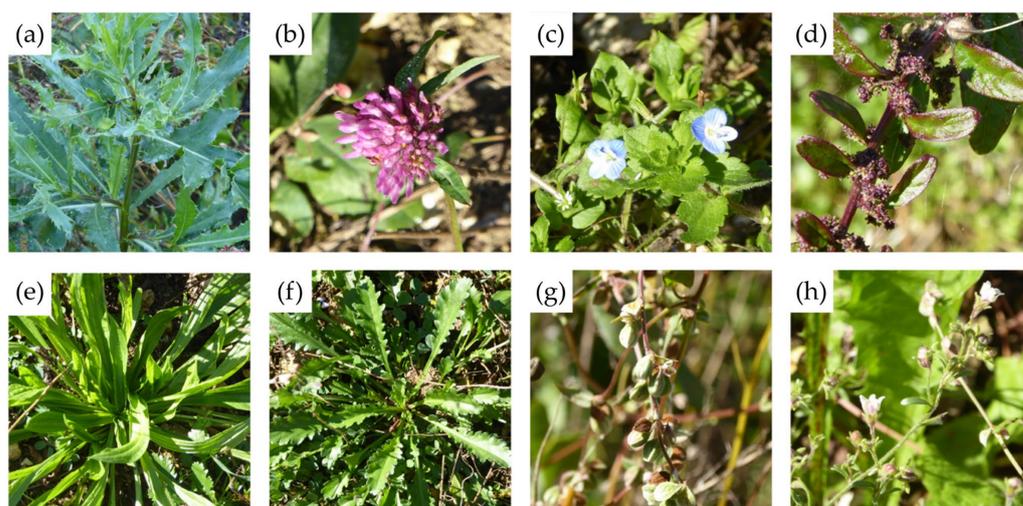


Figure A1. Weeds that were observed in camelina and calendula plots of the field trial at Oberer Lindenhof. (a) *Cirsium arvense* L. scop. (Creeping thistle), (b) *Trifolium pratense* L. (Red clover), (c) *Veronica persica* Poir. (Persian speedwell), (d) *Lipandra polysperma* (L.) S. Fuentes, Uotila & Borsch (Manyseed goosefoot), (e) *Plantago lanceolata* L. (Ribwort plantain), (f) *Leucanthemum vulgare* (Vaill.) Lam. (Oxeye daisy), (g) *Fallopia convolvulus* (L.) Á. Löve (Black bindweed), (h) *Chaenorhinum minus* (L.) Lange (Small toadflax). Plant species were determined using Pl@ntNet™ (2022).

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