Features of quality management of industrial hemp products (*Cannabis sativa* L.)

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ABSTRACT

A brief review of current research on oil and protein content in industrial hemp seeds is presented. One of the main factors limiting the development of hemp production is identified as the long-term ban on cultivation, which slowed the improvement of agronomic technologies. The study aimed to assess the effects of fertilization, growth stimulants, sowing rate, and preceding crops on seed quality indicators of industrial hemp. Two experimental schemes were implemented. In the first scheme, factor A included mineral fertilization systems: Polyphoska 8:24:24:9S (165 kg/ha) + UAN-32 (300 kg/ha) and Ecoplant (200 kg/ha) + UAN-32 (300 kg/ha). Factor B involved seed and foliar treatments with growth stimulants, including Humifield, 1R Seed Treatment, Zinovii Grand, and their combinations. The second scheme evaluated the effects of preceding crop (winter wheat, maize, industrial hemp), seed sowing rate (1.0 and 2.0 million seeds/ha), and pre-sowing seed treatment with Zinovii Grand. All treatments were arranged in a randomized design. A stable positive correlation between the duration of the biological maturity period and oil content was established (r = 0.27–0.79), indicating that extending the vegetation period through optimized plant nutrition may effectively enhance oil accumulation. Regression models suggested that, within the studied Ukrainian agroclimatic context characterized by unstable moisture supply, certain management combinations may allow concurrent increases in straw and seed yield while maintaining—and in some cases modestly improving – oil and protein contents; however, extrapolation to other climatic zones requires additional validation. The application of Ecoplant combined with UAN-32 increased oil content by 0.6% compared with Polyphoska-based fertilization. Foliar application of Zinovii Grand and 1R Seed Treatment increased oil content by approximately 0.5%, particularly under less effective fertilization regimes. Oil content was primarily determined by pre-sowing seed treatment, which contributed more than 70% to its formation, while sowing rate had no significant effect. The influence of the preceding crop averaged 9% over three years, reaching 19% in individual seasons. Protein content was affected by a broader range of factors and their interactions. Pre-sowing seed treatment increased oil and protein contents relative to the untreated control; in several treatment combinations, oil content exceeded 30% and protein content exceeded 25%.

Keywords: industrial hemp, oil content, protein content, fertilization, correlations.

INTRODUCTION

The uniqueness of industrial hemp lies in the practically zero-waste nature of its production, as almost all parts of the plant can be utilized for food, textile, or medicinal purposes. Even when hemp is cultivated on soils contaminated with heavy metals, only negligible amounts of Cd, Pb, and Zn are transferred into the fiber, which confirms its suitability for safe industrial use (De Vos et al., 2023). In addition, organic cultivation technologies of fiber hemp have been shown to improve soil agrochemical and bioecological properties while maintaining stable crop performance (Pylypchenko et al., 2023a). Fiber quality plays a crucial role in the production of modern construction and composite materials, including glass fiber–reinforced products (Trey et al., 2019).

During the relatively short period of revival of the hemp industry, global demand for hemp-based food products has been steadily increasing. The component composition of hemp oil is particularly complex; it contains palmitic, stearic, oleic, linoleic, and linolenic acids, including polyunsaturated omega-3 and omega-6 fatty acids, and is also rich in antioxidants, phytosterols, vitamins, and bioactive compounds (Frankowski et al., 2023). The ratio of these components is significantly influenced by varietal characteristics and agrotechnical practices, including sowing rate, harvesting time, and genotype–environment interactions. Under organic growing conditions, additional effects of soil fertility management and biological interactions on hemp seed quality indicators have been reported (Pylypchenko et al., 2023b).

Harvesting time is considered one of the most influential technological factors affecting seed oil composition and quality parameters (Marzocchi and Caboni, 2020). At the same time, cultivar-specific responses to environmental conditions largely determine biomass accumulation, flowering behavior, and oil productivity (Aubin et al., 2016; Mi et al., 2020).

Genetic variability in hemp significantly affects morphological traits, flowering dynamics, and biomass quality, highlighting the importance of genotype selection under specific environmental conditions (Petit et al., 2020). Similar conclusions were reported for hemp grown in different European regions, where yield and quality indicators varied substantially among cultivars (Habán et al., 2022).

As noted by Tariq et al. (2023), genotype–environment interactions should be studied in the context of global climate change, particularly considering shifts in temperature and radiation regimes. Special attention must be paid to photoperiod conditions, which should not be shorter than 13 h 40 min during the vegetation period to ensure normal phenological development and stable yields (Hall et al., 2014).

In different years, genotype–environment interactions may cause considerable variation in hemp straw yield, while having a relatively minor effect on fiber quality. According to Vandepitte et al. (2020), fiber tensile strength typically remains within the range of 37.6–45.3 cN/tex, even under variable growing conditions.

Hemp seeds are characterized by high feed and nutritional value. Klir et al. (2019) reported that the inclusion of hemp cake in ruminant diets increases milk fat content when applied at 480 g/day for small ruminants, while for dairy cows the effective rate is 143 g/kg of dry matter. The addition of 10–20 % hemp seeds to poultry feed was also shown to increase yolk fat content (Klir et al., 2019).

Even hemp grown primarily for textile purposes must account for the formation of primary and secondary fibers and their non-uniform distribution along the stem. The proportion of secondary fiber, which is generally characterized by lower tensile strength, is considered one of the key factors limiting overall fiber quality. Similar patterns were observed in studies linking flowering behavior with fiber quality formation (Salentijn et al., 2019).

Secondary fiber development is largely determined by plant biomass and growth dynamics. According to Westerhuis et al. (2019), increased plant weight promotes secondary fiber formation, which may negatively affect fiber quality. The combined influence of genotype and seeding rate on fiber quantity and quality has also been confirmed under different agroecological conditions (Jankauskienė et al., 2017).

Recent studies emphasize the high sensitivity of hemp cultivars to spatial and temporal variability in field conditions, reinforcing the need for adaptive management strategies (Hammami et al., 2022). Cultivar performance also varies depending on end-use orientation, such as fiber, seed, or dual-purpose production systems (Rahemi et al., 2021; Jankauskienė and Gruzdevienė, 2015).

According to Campiglia et al. (2017), sowing rate and nitrogen nutrition level significantly affect fiber tensile strength and agronomic performance. Ribeiro et al. (2023) further demonstrated that mechanical properties of hemp fibers are strongly influenced by both plant density and cultivation parameters.

Studies by Livingstone et al. (2022) confirmed that increased plant density leads to reduced stem diameter and increased internode length, which may indirectly affect fiber quality. Similar conclusions regarding the effects of seeding rate, fertility, and cultivar were obtained under North American growing conditions (Overbaugh, 2019).

The role of nitrogen in shaping seed quality and oil composition remains insufficiently studied. Tedeschi et al. (2020) showed that while urea fertilization had little effect on seed quality, it contributed to reduced N_2O emissions. A broader synthesis by Kaur et al. (2023) confirmed that nitrogen rates from 0 to 240 kg/ha did not

significantly increase seed mass but enhanced protein and oil content.

In dual-purpose hemp cultivation, delayed seed maturation leads to a decrease in bast fiber proportion and an increase in secondary fiber. Fibers obtained at the onset of flowering exhibit the highest tensile strength, which progressively declines as seed maturity advances (Liu et al., 2015; Mazian et al., 2019). The management of hemp agrocenoses aimed at obtaining both straw and seed yield can be supported by predictive models based on artificial neural networks. Such models demonstrate relatively high accuracy (74–91%) in yield forecasting (Frankowski et al., 2022; Hesami et al., 2021). However, studies focused on predicting and managing quality parameters remain limited (Sieracka et al., 2023).

An analysis of recent scientific publications on the formation of quality indicators of hemp straw, fiber, seeds, and nutrient content reveals a significant lack of comprehensive information. This deficiency is observed across all hemp-producing countries and regions, regardless of their level of industrial development.

To implement the research program, a relatively broad review of theoretical and empirical sources on dual-purpose industrial hemp cultivation was conducted (Pylypchenko et al., 2023a; Pylypchenko et al., 2023b; Sieracka et al., 2023). This synthesis indicates that, despite the gradual return of hemp into commercial production, plant nutrition strategies aimed at controlling product quality across contrasting agroclimatic zones remain insufficiently resolved. Relevant studies address these issues in South Asia (Tariq et al., 2023) as well as in a range of European countries, including Belgium (Vandepitte et al., 2020), Croatia (Klir et al., 2019), the Netherlands (Westerhuis et al., 2019; Vandepitte et al., 2020), Lithuania (Jankauskienė & Gruzdevienė, 2015; Jankauskienė et al., 2017), Italy (Campiglia et al., 2017; Marzocchi & Caboni, 2020), and Poland (Frankowski et al., 2022; Frankowski et al., 2023). Similar discussions are also developing in other continents and hemispheres (Aubin et al., 2016; Mi et al., 2020; Overbaugh, 2019; Rahemi et al., 2021; Livingstone et al., 2022). Overall, the current literature is less a coherent scientific debate and more an accumulation of location-specific evidence on hemp cultivation under diverse climatic conditions. Notably, even within Ukraine, where many regions share broadly comparable climatic features, the available body of

replicated, long-term experimental data remains limited (Pylypchenko et al., 2023a; Pylypchenko et al., 2023b).

MATERIALS AND METHODS

In two experiments, in which fertilization and sowing rate were the main research factors, yield and the oil and protein content of industrial hemp seeds were determined.

Experimental design 1 included factor A: a1 – Polyphoska 8:24:24 + 9S (165 kg/ha) + UAN-32 (300 kg/ha); a2 – Ecoplant (200 kg/ha) + UAN-32 (300 kg/ha); and factor B: b1 – no treatment; b2 – Humifield (0.2 kg/t); b3 – 1R Seed Treatment (1 kg/t); b4 – Zinovii Grand (1 kg/t); b5 – Humifield (0.2 kg/t) + Humifield (0.2 kg/ha); b6 – 1R Seed Treatment (1 kg/t) + Ultra Boost (2 L/ha); b7 – Zinovii Grand (1 kg/t) + Zinovii Grand (2 kg/ha).

Experimental design 2 included factor A – preceding crop: a1 – winter wheat; a2 – maize; a3 – industrial hemp. Factor B – seed sowing rate, with the following levels: b1 – 1.0 million seeds/ha; b2 – 2.0 million seeds/ha. Factor C – pre-sowing seed treatment with growth stimulants: c1 – no treatment; c2 – Zinovii Grand (1 kg/t). The plot area was 300 m², the experiment was conducted in three replications, and the treatments were arranged in a randomized design.

RESULTS AND DISCUSSION

Analysis of the influence of agrotechnical factors on oil content in hemp seeds requires very high accuracy, since this trait, according to the research results, showed very narrow ranges of variation. Therefore, identifying the effects of individual factors and their interactions is rather complex and requires precise measurements.

Based on the analysis of variance of three-year data, fertilization was identified as the main factor exerting the greatest influence on oil content (Figure 1). When the year-to-year variability of oil content is included in the factor analysis, the combined effect of growing conditions accounts for more than 90% of the total variation. Thus, the key objective of managing seed quality formation with respect to this parameter is the development of agronomic practices that allow the precise application of agrotechnical factors to ensure stability or, preferably, an increase in oil content.

The second most influential factor was the interaction between weather conditions of the growing season and fertilization. Other combinations of factor effects were statistically significant but, from a practical production standpoint, had a minor impact. Compared with these interactions, the effect of pre-sowing seed treatment was more pronounced. Therefore, this practice can be used to simultaneously increase seed yield and oil content.

The influence of year-specific growing conditions requires a more detailed clarification of the effects of individual factors. In 2023, the contribution of fertilization accounted for 44%, while pre-sowing seed treatment with growth stimulants contributed 52%. In 2024, the share of fertilization increased to 81%, whereas the contribution of pre-sowing seed treatment decreased to 17%. In 2025, the contribution of fertilization further increased to 91%, indicating the necessity of selecting fertilizers in accordance with the agrochemical properties of the soils.

Studies on the effects of preceding crops, seed sowing rates, and pre-sowing seed treatment on seed oil content formation showed that, over the three-year period, the pre-sowing seed treatment was the main factor influencing this trait (Figure 2). It is quite possible that this result was due to improved plant development at the early stages of vegetation; however, this effect requires more detailed investigation, which proved to be organizationally difficult under production-scale experimental conditions. In particular, attention should be paid to the formation and intensity of root system development.

The contribution of other, unidentified factors accounted for 8%. It should be noted that the integrated factor representing environmental conditions under which the experiment was conducted was excluded from the multifactorial analysis. When this factor is included in the analysis of variance, year-specific environmental conditions exhibit a decisive influence. From a production perspective, this does not directly affect oil content; however, for the development of effective ecological and economic technologies, as well as for other economically valuable traits, this factor must be carefully studied and its components identified as the true causes of the observed effects.

A similar pattern of factor influence was observed in 2023–2024: the effect of pre-sowing seed treatment accounted for 71%, while the selection of the preceding crop contributed 19%. The interaction between these factors was also statistically significant, although it accounted for only 4%. In 2025, the contribution of pre-sowing seed treatment reached 83%, whereas the choice of preceding crop had no effect on oil content formation.

It is necessary to highlight the behavior of the system of interrelationships among economically valuable traits when oil content in seeds is taken as the focal parameter. Correlation patterns varied from year to year (Figure 3). In 2023–2024, a
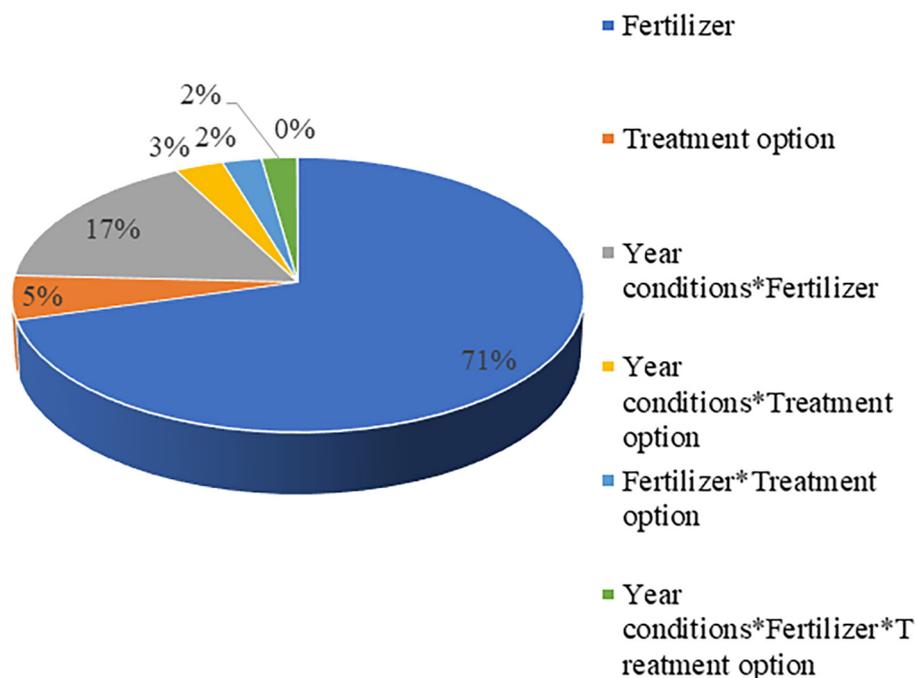

Figure 1. Influence of cultivation factors on oil content in seeds (2023–2025)
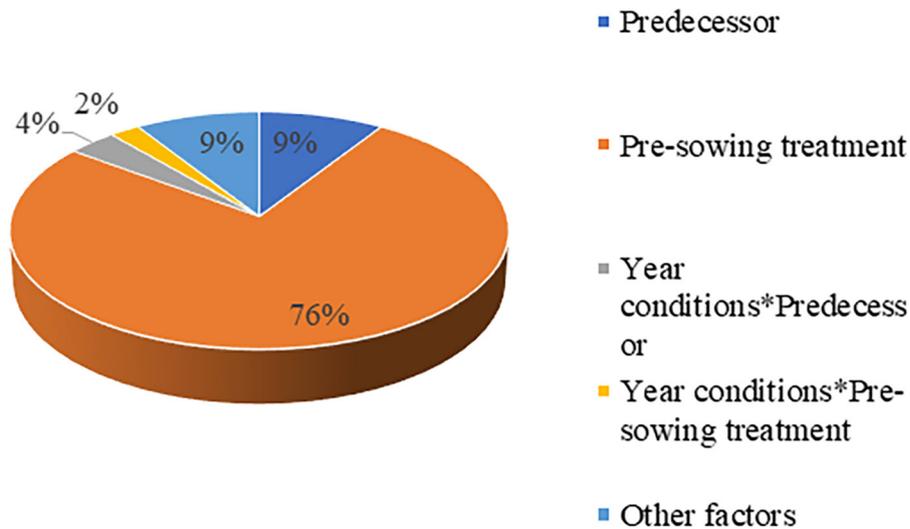
Figure 2. Contribution of cultivation factors to oil content formation

system of positive correlations was observed between yield indicators and plant height at harvest, as well as the duration of the period to biological maturity. In the subsequent year, only one correlation from the entire system remained – namely, with the duration of the biological maturity period. This variability also influenced the overall results obtained over the entire study period.

A characteristic feature of the relationship system between oil content and other traits was the high probability of strong positive correlations with straw and seed yield, plant height, and the duration of the maturation period (r = 0.73–0.85). Unlike yield indicators, this study made

it possible to establish a consistent relationship between traits regardless of growing conditions. The influence of the maturation period duration can be explained, in the author's opinion, by the cumulative nature of oil accumulation: the longer the plants vegetate, the greater the amount of oil – and possibly better values of other quality parameters – they are able to produce.

Quality indicators of seeds in many agricultural crops may be involved in systems of mutually limiting relationships, which can create difficulties in achieving the required yield while simultaneously maintaining the desired quality parameters. In this regard, an attempt was made
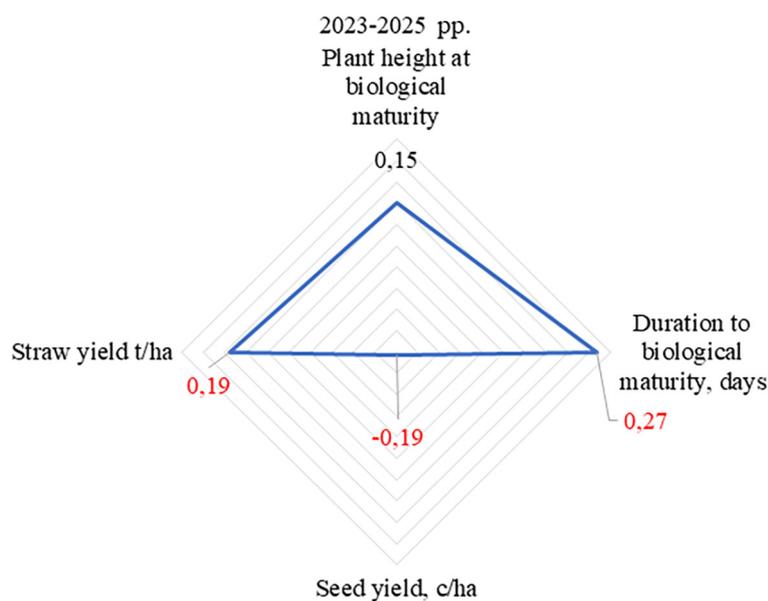

Figure 3. Correlation networks of oil content depending on the influence of economically valuable traits

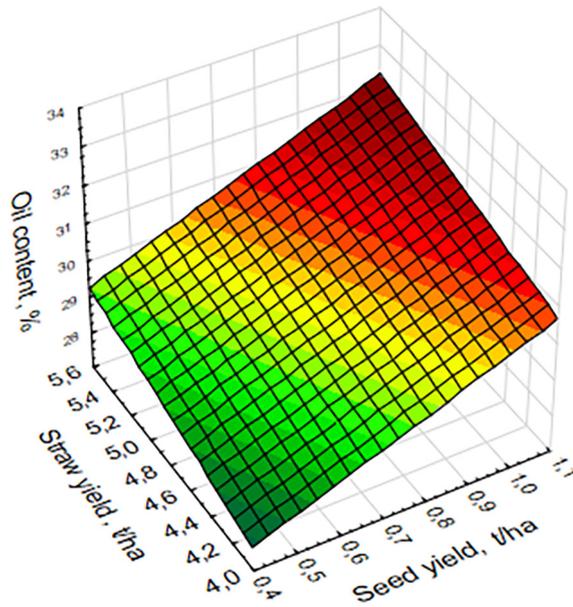## Oil content, % = 21,9601+4,2911*x+0,9965*y

Figure 4. Multiple regression plot of straw yield, seed yield, and oil content

to develop mathematical models describing the formation of oil and protein content quality in industrial hemp seeds.

Multiple regression analysis demonstrated that under conditions of unstable moisture supply, oil content in seeds was directly dependent on both straw and seed yield. Therefore, under these conditions, it is possible to apply approaches aimed at further increasing seed and straw productivity, which would be accompanied by

a subsequent increase in oil content (Figure 4). Both fertilizer application and the use of pre-sowing seed treatment with growth stimulants proved to be effective methods for managing oil accumulation in the experiment involving fertilizers and growth stimulants. The lowest oil content was recorded in the control treatments where growth stimulants were not applied. Over the period 2023–2025, oil content under the application of Ecoplant was 0.6% higher compared
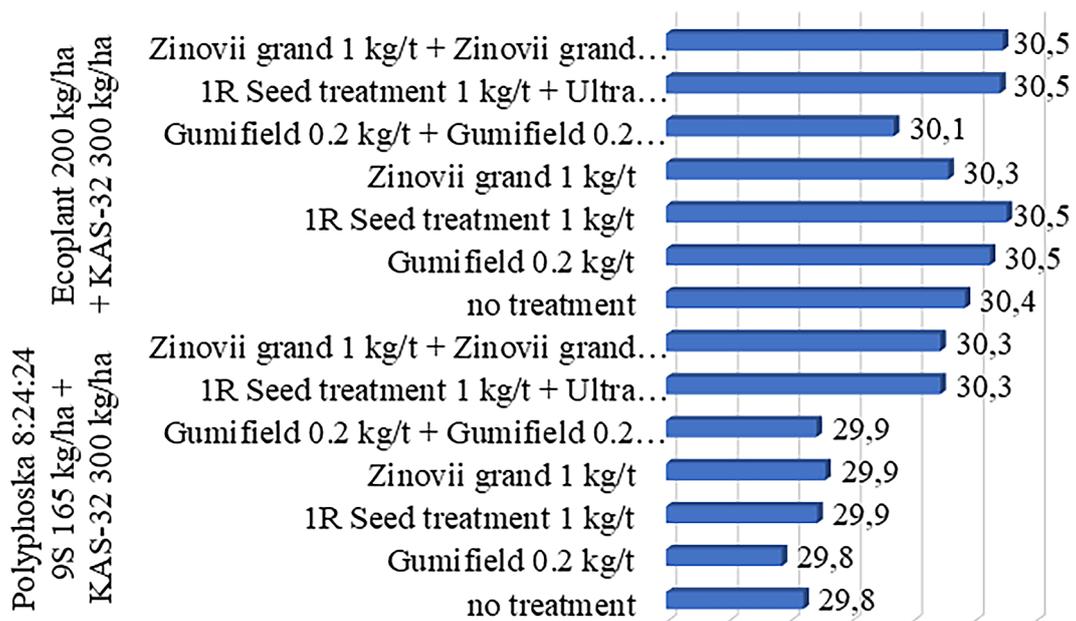

Figure 5. Oil content in hemp seeds depending on fertilization and the use of growth stimulants

with the use of Polyphoska 8:24:24:9S (Figure 5). The application of Humifield at a rate of 0.2 kg/t for pre-sowing seed treatment, as well as the use of the other two growth stimulants at a rate of 1 kg/t, did not result in a statistically significant increase in oil content. The effect of growth stimulants became evident only when they were applied in combination, including foliar application. However, this effect was observed only when Zinovii Grand and 1R Seed Treatment were used at application rates of 2 kg/ha. In treatments fertilized with Polyphoska 8:24:24:9S, the increase in oil content compared with the control reached 0.5%, whereas in treatments with Ecoplant this increase was not considered significant from a production perspective.

Thus, the effect of growth stimulants was more pronounced in the experimental treatments fertilized with Polyphoska 8:24:24:9S. This suggests that fertilizers for industrial hemp should be selected in accordance with the agrochemical characteristics of the soils, while the use of growth stimulants based on humic substances is a rational approach to improving plant nutrition, both for pre-sowing seed treatment and foliar application. The research results also indicate a higher efficiency of foliar application of growth stimulants at rates of approximately 2 kg/ha, which provided a statistically significant effect.

At the same time, it should be noted that scientific results are not always sufficiently convincing for agricultural production, which generally expects substantial yield increases. This is one of the reasons for the limited use of growth- and development-stimulating preparations, despite their potential to enhance crop productivity.

Seed sowing rates did not have a practical effect on oil content formation (Figure 6). In 2023 and 2024, a slight decrease in oil content was observed in treatments with a sowing rate of 2 million seeds/ha; however, in the first year of the study this decrease amounted to 0.21%, and in the following year to 0.17%, which had no agronomic or economic significance. In 2025, no economically meaningful change in oil content was observed either, although a slight increase of 0.16% was recorded.

Therefore, when the cultivar Hlesiia is used for food production under specific conditions, an increase in sowing rate has little effect on oil content, and attention should instead be focused on other economically valuable traits under the given growing conditions.

The absence of an effect of sowing rate on oil content formation in this study does not justify the assumption of similar patterns or effects for other cultivars. Varietal characteristics have a substantial influence on the complex of traits; therefore, it is necessary to study as many hemp cultivars as possible in order to develop cultivar-adaptive cultivation technologies.

Preceding crops had a much more pronounced effect on oil content formation, and according to the results of all years of research, the highest oil
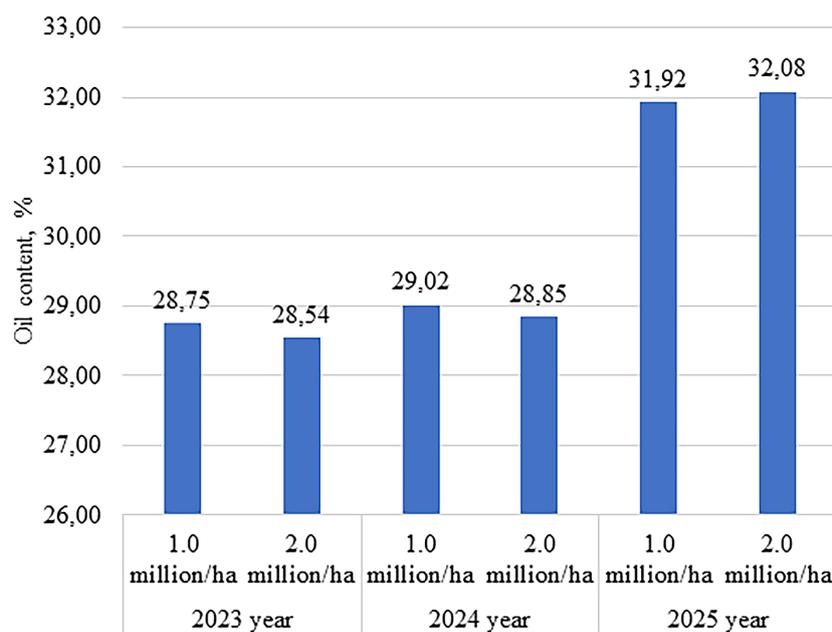

Figure 6. Dependence of oil content on seed sowing rate

content was observed in repeated hemp cropping (Figure 7). With regard to winter wheat and maize as preceding crops, no clear or consistent pattern was identified. In 2023, oil content in seeds of treatments following winter wheat was 0.2% higher compared with maize, which was within the margin of statistical error, whereas in 2024, oil content following maize was 0.34% higher. In 2025, no economically significant difference was established, and oil content was virtually identical.

Overall, it should be noted that oil content in hemp seeds proved to be a trait characterized by low variability, at least when the cultivar Hlesiia was used. It is quite possible that other cultivars currently used in production exhibit a much wider response range of this trait to factors such as preceding crop, sowing rate, or pre-sowing treatment. This indicates the need to expand research efforts and to form cultivar clusters with similar response norms within such groups.

Protein content showed much greater differentiation compared with the previous parameter; however, no clear pattern was identified during the research. Despite the fact that this trait was influenced by a much wider range of factors and their interactions, in 2023 the highest seed protein content was obtained at a sowing rate of 1.0 million seeds/ha, with a difference of 0.24% compared with the higher sowing rate (Figure 8).

In the following year of the study, the situation changed: higher protein content was obtained in treatments with a sowing rate of 2.0 million seeds/ha, exceeding the lower rate by 0.33%. In the final year of the experiment, the same average result was recorded across all treatments.

A clear and consistent pattern of the effect of pre-sowing seed treatment on protein content formation was observed in all years of the experiment (Figure 9). In 2023, the use of growth stimulants increased protein content by 1.07%, while in 2024 this increase amounted to 0.93%. In 2025, protein content was statistically similar among treatments; however, the tendency toward increased protein content was maintained.

Statistical analysis of the experimental results made it possible to identify the most effective treatments for increasing oil and protein content. The highest average values of oil and protein content in seeds were recorded in treatments where pre-sowing seed treatment with the growth stimulant Zinovii Grand (1 kg/t) was applied. Experimental treatments without this agronomic practice showed significantly lower values for these parameters across all experimental blocks, regardless of the preceding crop or seed sowing rate (Table 1).

Pre-sowing seed treatment increased oil and protein contents relative to the untreated control; in several treatment combinations, oil content exceeded 30% and protein content exceeded 25%. These effects were observed under the specific agroclimatic conditions of the study years and should not be directly extrapolated to other environments without additional multi-location validation.

Thus, protein content showed a similar dependence on cultivation factors as oil content; however, the number of influencing factors and their interactions was greater (Figure 10). The importance of pre-sowing seed treatment lies not only in its dominant direct effect (70%) but
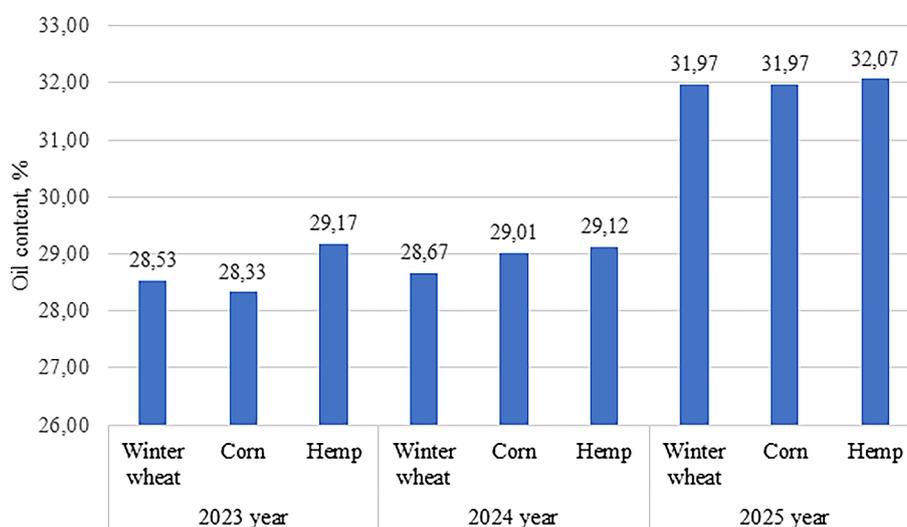

Figure 7. Dependence of oil content on the selection of the preceding crop
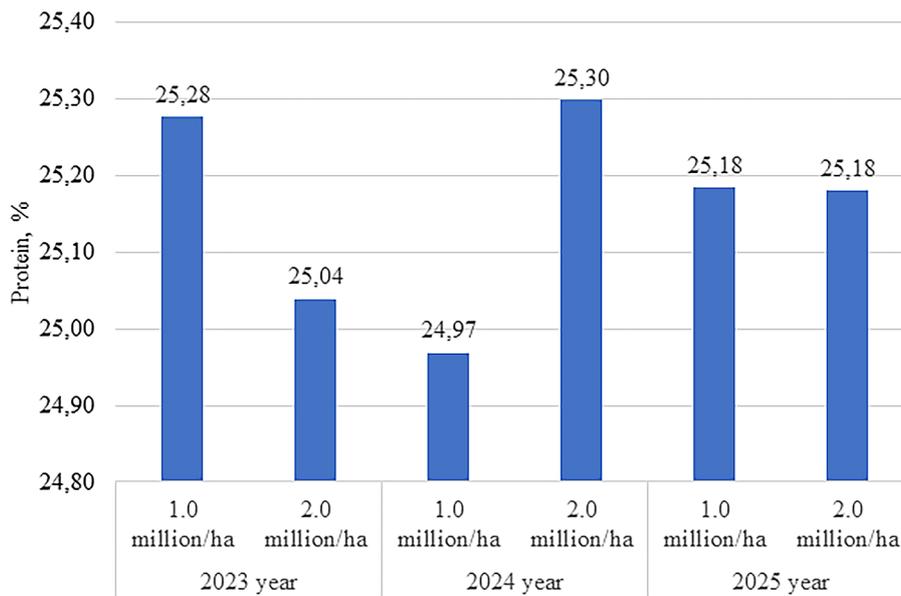
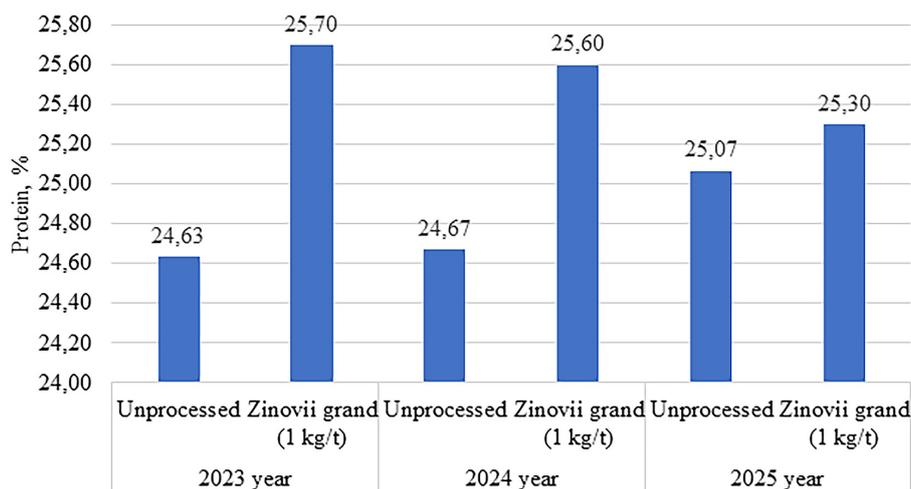**Figure 8.** Dependence of protein content on seed sowing rate

Figure 9. Dependence of protein content on the application of pre-sowing seed treatment with growth stimulants

also in the significance of its interactions with the complex of growing conditions, the selection of preceding crops, and the combined effect of these factors with seed sowing rates.

The results of quality indicator assessments showed that seed quality traits – oil and protein content – exhibited low dispersion. Under the applied fertilization system, choice of preceding crop, or seed sowing rate, it was not possible to substantially change these parameters. However, the research program was based on practical experience accumulated by producers after the long-term ban on hemp cultivation, as well as on recommendations from leading national research institutions. Within the system of interrelationships, it was established that in the experiment involving

preceding crops, sowing rates, and pre-sowing seed treatment, the limiting factor for oil content was the thousand-seed weight (Figure 11).

The conducted research made it possible to identify key regularities and specific features in the formation of seed quality indicators of industrial hemp under conditions of unstable moisture supply. The developed regression models demonstrated that oil and protein contents are characterized by weak mutual limitation, indicating the potential for their simultaneous increase.

For such predictive models, it is necessary to account for quantitative seed traits, particularly thousand-seed weight. The regression models obtained in this study suggest that oil and protein contents exhibited only weakly mutually

Table 1. Influence of agrotechnical factors on the formation of seed quality indicators (2023–2025)

| Preceding crop (B)	Seed sowing rate (C)	Pre-sowing treatment (D)	Oil content, %	Protein content, %
Winter wheat	1.0 million seeds/ha	No treatment	29.27	24.65
		Zinovii Grand (1 kg/t)	30.10	25.26
	2.0 million seeds/ha	No treatment	29.24	24.82
		Zinovii Grand (1 kg/t)	30.27	25.22
Maize	1.0 million seeds/ha	No treatment	29.48	24.81
		Zinovii Grand (1 kg/t)	30.13	25.33
	2.0 million seeds/ha	No treatment	29.49	24.98
		Zinovii Grand (1 kg/t)	29.98	25.78
Industrial hemp	1.0 million seeds/ha	No treatment	29.92	24.85
		Zinovii Grand (1 kg/t)	30.49	25.96
	2.0 million seeds/ha	No treatment	29.65	24.64
		Zinovii Grand (1 kg/t)	30.42	25.64
HIP_{05} A			0.17	-
HIP_{05} B			0.13	0.08
HIP_{05} D			0.14	0.07
HIP_{05} AB			-	0.14
HIP_{05} AC			-	0.12
HIP_{05} BC			-	0.13
HIP_{05} AD			0.23	0.20
HIP_{05} BD			-	0.21
HIP_{05} ABC			-	0.17
HIP_{05} ACD			-	0.19
HIP_{05} BCD			-	0.20
HIP_{05} ABCD			-	0.29
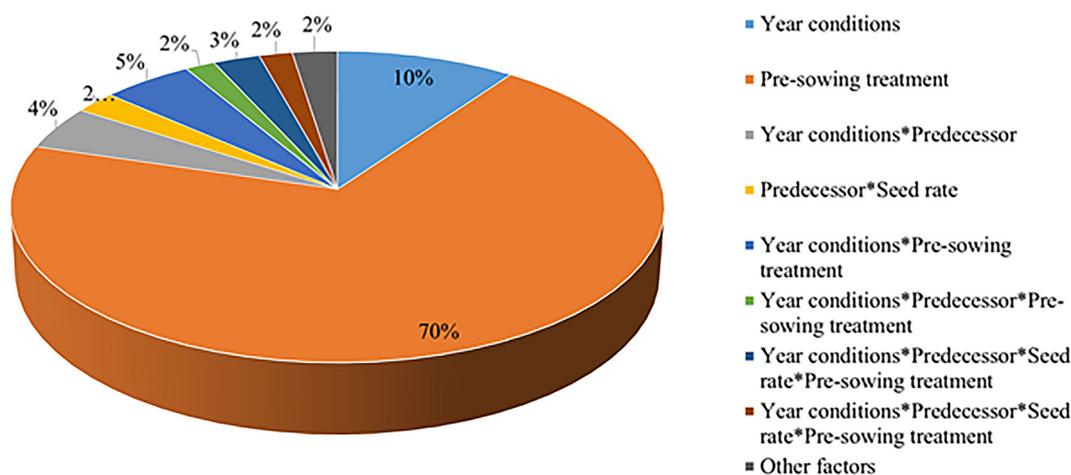
Figure 10. Influence of cultivation factors on protein content formation

constraining behavior under conditions characterized by unstable moisture supply. However, this inference is conditional: in other soil–climatic settings with more favorable and stable water availability, the relationship between oil and protein accumulation may plausibly become nonlinear, and potential trade-offs cannot be excluded without additional multi-site validation. Based on the analysis of interrelationships among economically valuable traits, it can be concluded that further refinement of fertilization strategies may be feasible, provided that fertilizer types

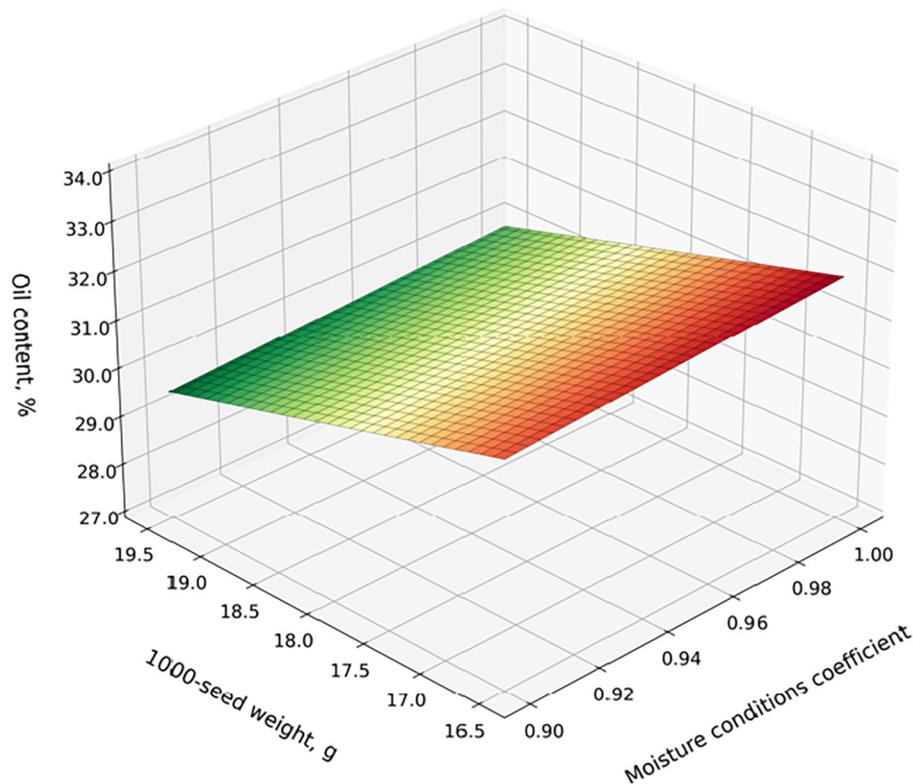Oil content, % = 38.6998 + 4.0702·x − 0.6588·y

Figure 11. Multiple regression plot of oil content as a function of seed yield and thousand-seed weight

and preceding crops are properly selected. Such an approach enables an increase in both seed and straw yield of industrial hemp while maintaining or enhancing oil and protein content in the seeds.

The obtained results allowed the identification of general trends in the formation of protein and oil content in industrial hemp seeds. At the same time, it should be emphasized that literature data reported by different authors often show considerable variability. This inconsistency is primarily associated with the limited availability of long-term experimental data, largely resulting from the prolonged prohibition of hemp cultivation in many countries. In addition, agroclimatic factors play a decisive role: due to its high ecological plasticity, hemp is cultivated across diverse geographical zones, where raw material utilization depends on local traditions, specific production objectives of the hemp industry, and the economic conditions of individual countries. Consequently, different sets of cultivars are selected for cultivation.

As shown by the present study, the substantial contribution of uncontrolled environmental factors leads to high variability in the effects and

interactions of both regulated and unregulated factors on yield formation and product quality (Tariq et al., 2023; Vandepitte et al., 2020). It should also be noted that agricultural producers often demonstrate a cautious attitude toward scientific recommendations. Despite statistically significant improvements in seed quality indicators observed under experimental conditions, producers usually expect more pronounced effects. This restrained response is further explained by insufficient economic incentives, as market prices for seeds with increased protein and oil content remain weakly differentiated.

Nevertheless, the results obtained confirm the possibility of managing the formation of key quality indicators of industrial hemp seeds. Under the agroclimatic conditions of Ukraine, the production of high-quality raw materials is entirely feasible, which is largely associated with the long photoperiod. At the same time, the present study did not allow a clear differentiation of the individual roles of specific nutrients, which is consistent with the conclusions reported by Tedeschi et al. regarding the limited influence of nitrogen on oil content and its component composition (Tedeschi

et al., 2020). According to Kaur et al. (2023), the application of high nitrogen rates (0–240 kg/ha) contributes to an increase in seed protein content. In the present experiments, UAN-32 was used as the main nitrogen source, and the observed increase in protein content was associated with the application of growth stimulants, which likely enhanced nitrogen uptake and utilization efficiency under the studied conditions.

STUDY LIMITATIONS AND TRANSFERABILITY

The experiments were conducted under the specific photoperiod, climatic regime, and soil conditions of Ukraine, which may shape both yield formation and seed composition. Because direct comparisons with other agroclimatic zones were not included, the international transferability of the quantitative effects reported here is limited. Future work should test the identified factor structure and the regression relationships in multi-location trials spanning contrasting photoperiod and moisture regimes to evaluate the stability of response patterns and potential trade-offs among yield and quality traits.

CONCLUSIONS

The presence of a stable positive correlation between the duration of the biological maturity period and oil content (r = 0.27–0.79) indicates that one of the effective methods for increasing oil content is the optimization of plant nutrition aimed at extending the vegetation period of hemp plants. This can be achieved through the selection of fertilizers according to the agrochemical characteristics of the soil.

The application of Ecoplant fertilizer at a rate of 200 kg/ha in combination with UAN-32 at 300 kg/ha increased seed oil content by 0.6% compared with the use of Polyphoska 8:24:24:9S. The plant growth stimulants Zinovii Grand and 1R Seed Treatment, applied foliarly at a rate of 2 kg/ha, also contributed to an increase in oil content by 0.5%, with a more pronounced effect observed in treatments with comparatively less effective fertilization. Oil content largely depends on pre-sowing seed treatment, the contribution of which may exceed 70%. For the industrial hemp cultivar Hlesiia, seed sowing rates did not have a

significant effect on oil content formation, while the effect of preceding crop selection accounted for 9% over the three-year study period. In certain years, the contribution of this factor reached 19%.

Protein content was influenced by a greater number of factors and their interactions compared with oil content. Pre-sowing seed treatment increased oil and protein contents relative to the untreated control; in several treatment combinations, oil content exceeded 30% and protein content exceeded 25%.

The regression models indicate that under unstable moisture supply (as observed in the study years), management-driven increases in straw and seed yield can be compatible with maintaining seed oil and protein contents and, in some cases, with small improvements. However, this conclusion should be interpreted as context-specific and requires confirmation in other soil–climatic zones and moisture regimes.

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