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Assessing the Impact of Lignite-Based Rekulter Fertilizer on Soil Sustainability: A Comprehensive Field Study

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Abstract: This study aimed to investigate the impact of Rekulter, a lignite-based fertilizer, on various soil parameters, with a focus on promoting sustainable agricultural practices. A multi-year field trial was conducted in Klon, Poland, employing potentiometric techniques, spectrophotometry, and gas chromatography-mass spectrometry to analyze soil samples. Established laboratory procedures were used to assess pH value, sorption properties, granulometric composition, organic carbon content (OC), total nitrogen (TN), polycyclic aromatic hydrocarbons (PAHs), phenolic compounds (PCs), and the fractional composition of organic matter. Hypothesis-driven experiments, including Analysis of Variance (ANOVA) and Tukey's HSD post hoc tests, were utilized to examine the effects of Rekulter application on soil characteristics. Significant differences were found in organic carbon (OC), total nitrogen (TN), polycyclic aromatic hydrocarbons (PAHs), phenolic compounds (PCs), and fractional organic matter composition among the Rekulter variants. This study underscores the dose-dependent effects of Rekulter on soil properties and provides insights into optimizing application rates for sustainable soil management. Recommendations include tailoring agricultural interventions based on soil characteristics and environmental considerations, integrating organic amendments with mineral fertilizers, and promoting balanced approaches to reclamation. This research contributes to ongoing efforts to improve agricultural sustainability and mitigate environmental impacts, guiding practices that balance productivity with environmental stewardship.

Keywords: Rekulter; lignite-based fertilizer; sustainable agriculture; soil fertility; dose-dependent effects; soil sustainability; agricultural interventions; soil management

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1. Introduction

Soil fertility and management are critical components of sustainable agriculture [1], influencing crop productivity [2], environmental sustainability [3], and food security [4]. The enhancement of soil fertility and health stands as a critical objective in sustainable agriculture, necessitating ongoing exploration of soil modifications to improve agricultural productivity [3,5]. Several scientific papers have extensively covered this topic [3,5]. Kibret et al. [3] contribute to this pursuit by investigating the correlation between land use types and specific soil physicochemical properties, aligning their research with the imperative need for continuous advancements in soil amendments to boost productivity. Lehmann et al. [5] focus on optimizing soil fertility and health by manipulating the soil microbiome to improve soil health and plant fertility. Thapa et al. [6] emphasize micronutrient management to enhance soil fertility, health, and soybean yield, contributing to the enhancement of agricultural sustainability. Akimbekov et al. [7] assess the efficacy of lignite-based fertilizer, particularly Rekulter, as a source of humic substances for soil amendment and fertility management, evaluating its impact on soil fertility and environmental factors, such as the formation of polycyclic aromatic hydrocarbons (PAHs) and phenolic compounds (PCs), through a comprehensive multi-year field trial. Ciarkowska et al. [8] compare the effects of lignite-derived humic acids and farmyard manure (FYM) on soil properties and vegetable yield, highlighting the benefits of lignite as a soil amendment. Dębska et al. [9] study the effects of fertilization with brown coal on Haplic Luvisol humic acids, contributing to the understanding of lignite-based fertilizers as effective soil amendments.

The literature suggests that organic amendments, including lignite-based fertilizers, can influence soil pH [10], organic carbon content [11], nutrient availability [12,13], and microbial activity [14]. These amendments have been shown to enhance soil fertility [15], improve crop yields [16], and promote sustainable agricultural practices [17]. Lignite-based fertilizers, such as Rekulter [8], have gained attention as potential soil amendments due to their organic content and nutrient-rich composition [18]. Amidst the significant impact of soil amendments on agricultural outcomes, a discernible research gap remains, however, with respect to the comprehensive evaluation of lignite-based fertilizers, with a focus on reclaimers, over an extended temporal range [19]. For example, the study by Amoah-Antwi et al. [19] discusses how amendment with Rekulter improves soil conditions and ameliorates potential problems, highlighting its potential impact on soil quality over time [19]. Understanding the effects of Rekulter application on soil properties is essential for optimizing agricultural practices and mitigating environmental impacts [18,20]. The complex interplay between different reclamation rates and soil properties, coupled with potential environmental risks, requires focused investigation. The specific effects of Rekulter application on soil properties remain unclear, particularly regarding its dose-dependent responses and long-term impacts. Therefore, this study aims to address a critical knowledge gap by pursuing a twofold objective: to provide a nuanced exploration of the influence of Rekulter on various soil properties and its long-term impacts, as well as to determine the dose-dependent effects of Rekulter with the goal of identifying the optimal application rates for sustainable soil management practices. To address this knowledge gap, this research employs a comprehensive analytical approach to thoroughly evaluate soil samples collected during a multi-year field experiment conducted in Klon, Poland. The findings of this study will contribute to the existing knowledge base on soil fertility, organic amendments, and sustainable agriculture, ultimately supporting soil health and facilitating optimized, informed, and prudent agricultural practices through guidance on dose optimization. By examining soil pH, acidity, sorption properties, granulometric composition, organic carbon content, total nitrogen levels, PAH and PC content, and fractional composition of organic matter, we seek to elucidate the complex interplay between Rekulter application and soil dynamics.

The application of lignite-based fertilizers has garnered attention due to its potential impact on soil properties. Both short-term and long-term applications of these fertilizers at varying doses can lead to significant changes in soil characteristics. Previous studies have indicated that lignite-based fertilizers, such as Rekulter, can influence soil pH, organic carbon content, nitrogen levels, and contaminant concentrations [20,21]. Short-term application may result in immediate changes, such as alterations in soil acidity and nutrient availability, while long-term application can lead to more profound effects, including improvements in soil fertility and structure [22]. The dosage of lignite-based fertilizers plays a crucial role in determining the extent of their impact on soil properties. Higher doses may result in greater changes in organic matter content and nutrient levels, while lower doses may have more subtle effects [23]. Understanding the short-term and long-term effects of lignite-based fertilizer application on soil properties is essential for sustainable soil management practices and agricultural productivity. Building on this, the study examines a series of hypotheses to investigate the impacts of Rekulter use on various soil characteristics. Firstly, it is hypothesized that varying levels of Rekulter application will induce changes in soil pH and acidity, as underscored by Kumar Dewangan et al. [10], Msimbira and Smith [24], Parikh and James [25], and Muneer et al. [14]. Soil pH, a critical factor for nutrient availability, microbial activity, and overall soil health, is emphasized in these studies. For instance, the importance of maintaining soil pH within the optimal range of 6.0

to 7.0 for nutrient availability and microbial activity is emphasized by Kumar Dewangan et al. [10]. Similarly, Msimbira and Smith [24] highlight the direct influence of pH variations on nutrient availability and microbial community structure. Secondly, it is proposed that Rekulter application will affect soil sorption properties, as discussed by Agim et al. [12], Głąb et al. [13], Albano et al. [26], and Larney and Angers [27]. Organic amendments, such as Rekulter, can influence nutrient retention and availability, as highlighted in these studies. Agim et al. [12] emphasize the role of organic matter in moisture retention and nutrient availability, while Głąb et al. [13] discuss how organic amendments can influence soil nutrient retention and availability. Thirdly, it is posited that Rekulter application may lead to changes in soil particle size distribution, as explored by Agim et al. [12], Cui et al. [11], and Dong et al. [28]. These studies investigate the impact of organic amendments on soil texture, highlighting their influence on soil properties. Fourthly, it is hypothesized that Rekulter application will result in variations in organic carbon (OC) and total nitrogen content (TN), as suggested by Cui et al. [11], Traunfeld [29], Su et al. [30], and Li et al. [31]. Organic amendments contribute to soil organic matter (SOM), thereby affecting OC and TN levels, as discussed in these studies. Fifthly, it is proposed that Rekulter application may lead to differential concentrations of soil contaminants (i.e., PAHs and PCs), as investigated by Yang et al. [32]. Organic materials, like Rekulter, have the potential to introduce PAHs and PCs into the soil, as discussed by Yang et al. [32]. Lastly, it is hypothesized that Rekulter application will influence the fractional composition of humic substances, as highlighted by Hayes and Swift [33], Hricíková et al. [34], Lanno et al. [35], Ampong et al. [36], and Trevisan et al. [37]. These studies emphasize the responsiveness of humic substances to organic inputs and their roles in soil health and fertility. These six hypotheses provide a comprehensive framework for understanding the multifaceted impacts of Rekulter on soil properties. Further analysis could reveal dose-dependent effects and potential long-term impacts of Rekulter application, thereby informing agricultural practices for enhanced sustainability and productivity.

In summary, this study is significant in its ability to provide a deeper understanding of the long-term effects of lignite-based soil amendments on various aspects of soil health and environmental sustainability. By conducting a thorough investigation of dose-dependent responses and long-term soil dynamics, this research aims to shed light on the influence of these fertilizers on soil fertility, humic matter transformation, and overall sustainable environmental management. In addition, this study addresses potential environmental risks associated with the formation of contaminants, such as PAHs and PCs, based on the results of the multi-year field trial. This comprehensive assessment will contribute to the development of more informed and responsible agricultural practices, ultimately promoting the sustainable use of soil resources.

2. Materials and Methods

The study of the impact of Rekulter on soil properties necessitated the selection of research sites for the implementation of a multi-year field trial. The field experiment was carried out to gather samples extracted from the soils for subsequent physicochemical and spectrometric analyses. These analyses encompassed the determination of various properties, including the pH value and acidity, sorption properties, granulometric composition, OC, TN, content of PAHs and PCs, and fractional composition of organic matter.

2.1. Research Materials

2.1.1. Location of the Multi-Year Field Trial

Several critical factors were considered when selecting the field trial site, including soil properties, climatic conditions, environmental factors, experimental design, accessibility, land ownership and permissions, and spatial and temporal variation. The experiment was conducted in Klon, Poland (53°27′55′′ N 21°16′58′′ E; see Figure 1) and was designed to study the long-term effects of Rekulter on soil properties. In this 22-year trial, a one-time lignite fertilizer was applied at rates of 40, 80, and 160 t/ha to a rusty soil (Arenosols).

This soil type is characterized by loose sand with very low water holding capacity, high permeability, low pH, and poor sorption properties.

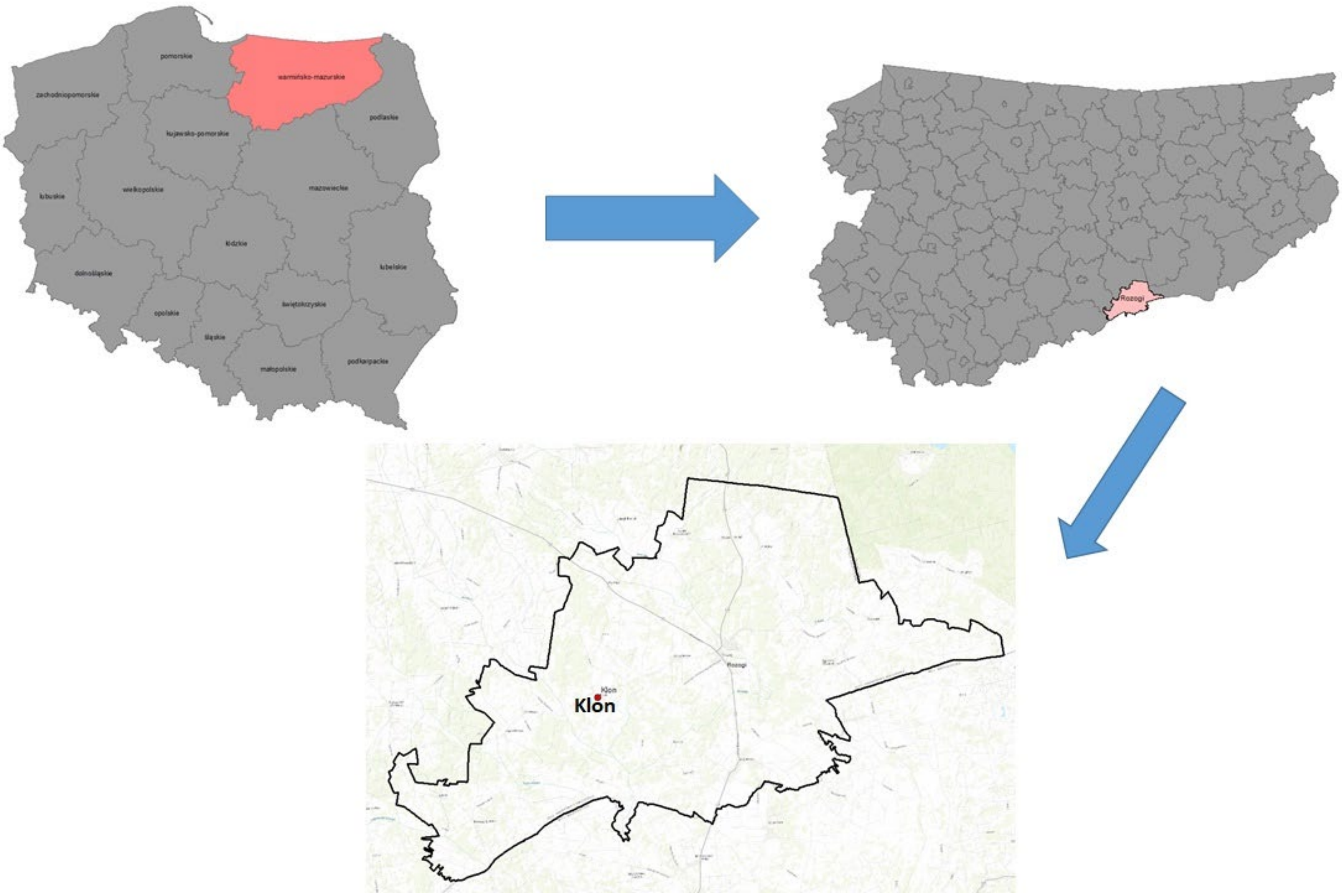

Figure 1. Location of the multi-year trial (53°27′55″ N 21°16′58″ E); source: own elaboration.

2.1.2. Description of the Experimental Design

The study was conducted in accordance with established scientific protocols to ensure rigor and reliability of the findings [20,38]. The experimental design aimed to investigate the impact of different doses of Rekulter on soil properties over a 22-year period. The study utilized a Randomized Complete Block Design (RCBD), which involved dividing the experimental field into four adjacent sub-blocks, numbered 1, 2, 3, and 4. Figure 2 shows the experimental fields in Klon (Poland).

Such spatial division allowed for the systematic grouping of similar areas to enhance experimental control and facilitate data interpretation. The division of the field into sub-blocks offered several scientific benefits, including enhanced homogeneity, controlled variation, increased statistical power, and improved interpretation of treatment effects. By grouping similar areas together within each sub-block, potential sources of variability such as soil type, topography, and microclimate were accounted for, leading to more precise and reliable experimental results. Within each sub-block, Rekulter treatments were randomly assigned to individual plots or areas, ensuring that each treatment (K1 = 0 t/ha—control, K2 = 40 t/ha—low dose, K3 = 80 t/ha—medium dose, K4 = 160 t/ha—high dose) was represented within each sub-block. This random assignment minimized bias and allowed for the assessment of treatment effects independent of specific environmental conditions. Each treatment was replicated five times within its corresponding sub-block to provide multiple data points for analysis and to enhance the reliability of the experimental results. Replication increased the precision of treatment effect estimates and allowed for more robust statistical inference. While the sub-block division served as a form of blocking, additional sources of variation within each sub-block were controlled through replication.

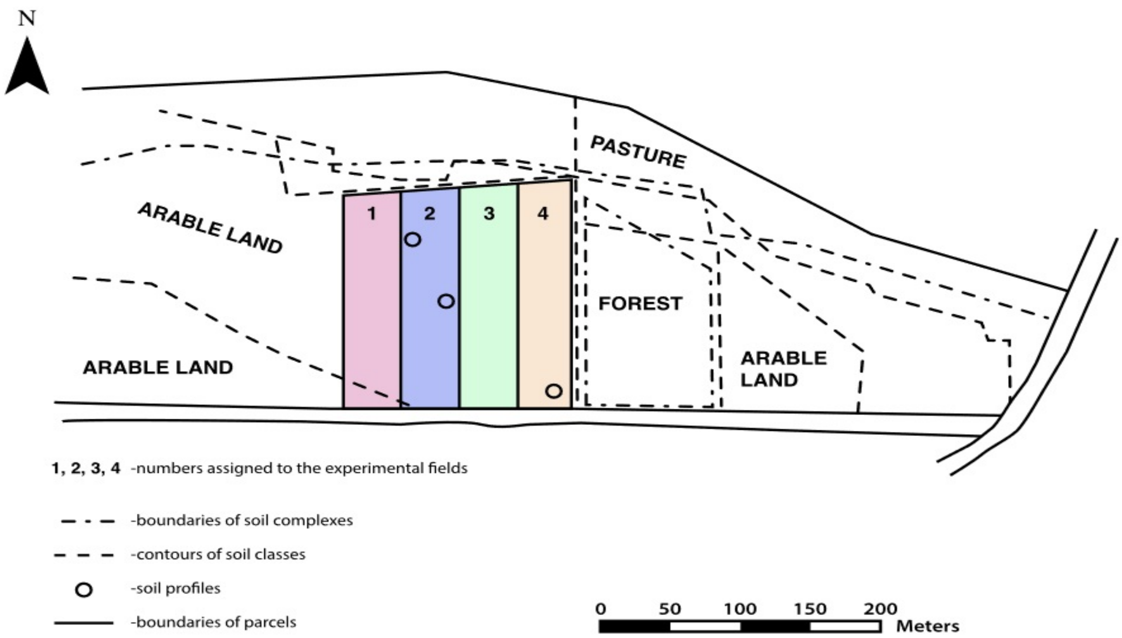

Figure 2. Experimental fields in Klon (Poland); source: own elaboration.

Soil samples were collected from each sub-block using an Egner stick, extracting samples from the 0–20 cm depth range. This standardized sampling approach ensured consistency across samples and facilitated the comparison of soil properties between treatments. The collected soil samples underwent thorough analysis to quantify various soil properties, including pH, nutrient levels, and organic matter content. Data analysis was performed using the principles of RCBD, with sub-blocks serving as experimental units. Statistical techniques appropriate for RCBD, such as analysis of variance (ANOVA), were employed to assess the significance of treatment effects while accounting for variability between sub-blocks.

By implementing the RCBD with a division into sub-blocks and random assignment of treatments, the experimental design provided a robust framework for evaluating the effects of Rekulter application on soil properties. The systematic grouping of similar areas within sub-blocks, combined with replication and randomization, enhanced the validity and reliability of the study findings, ultimately contributing to a more comprehensive understanding of Rekulter's impact on soil health.

2.2. Research Methods

2.2.1. Analysis of the Soil Samples Treated with the Lignite-Based Fertilizer (Rekulter)

During the course of the research study, soil samples were collected and subjected to a comprehensive set of analyses to determine various soil properties. The analyses included the determination of pH in H_2O and in 1 M KCl using the potentiometric method [22,23], hydrolytic acidity (Hh) and the sum of bases (S) using Kappen's method [39], cation exchange capacity (T) calculated from the hydrolytic acidity (Hh) and the sum of bases (S), OC with the use of the Tyurin method (a commonly used technique for quantifying OC in soil) [40], and TN using the Kjeldahl method (a well-established approach for measuring TN in various matrices, including soil) [41,42]. An overview of the Kjeldahl method for TN determination, including sample preparation, working scale, instrumentation, and quality control, has been described in the study by Sáez-Plaza et al. [41]. Black et al. [42] described the Kjeldahl method for the determination of TN in soils by providing a comprehensive review of different methods for the determination of inorganic forms of nitrogen in soils, including the steam distillation method, which is a variant of the Kjeldahl method. Other analyses included granulometric composition according to the Casagrande method modified by Prószyński [43], fractional composition of organic matter using the Tyurin method [40], and PAH and PC content using gas chromatography with mass spectrometric detection after extraction with dichloromethane according to the PB-16 method [44]. A schematic diagram of the multi-year experimental field study (indicating which analyses were performed and which parameters were measured) is shown in Figure 3.

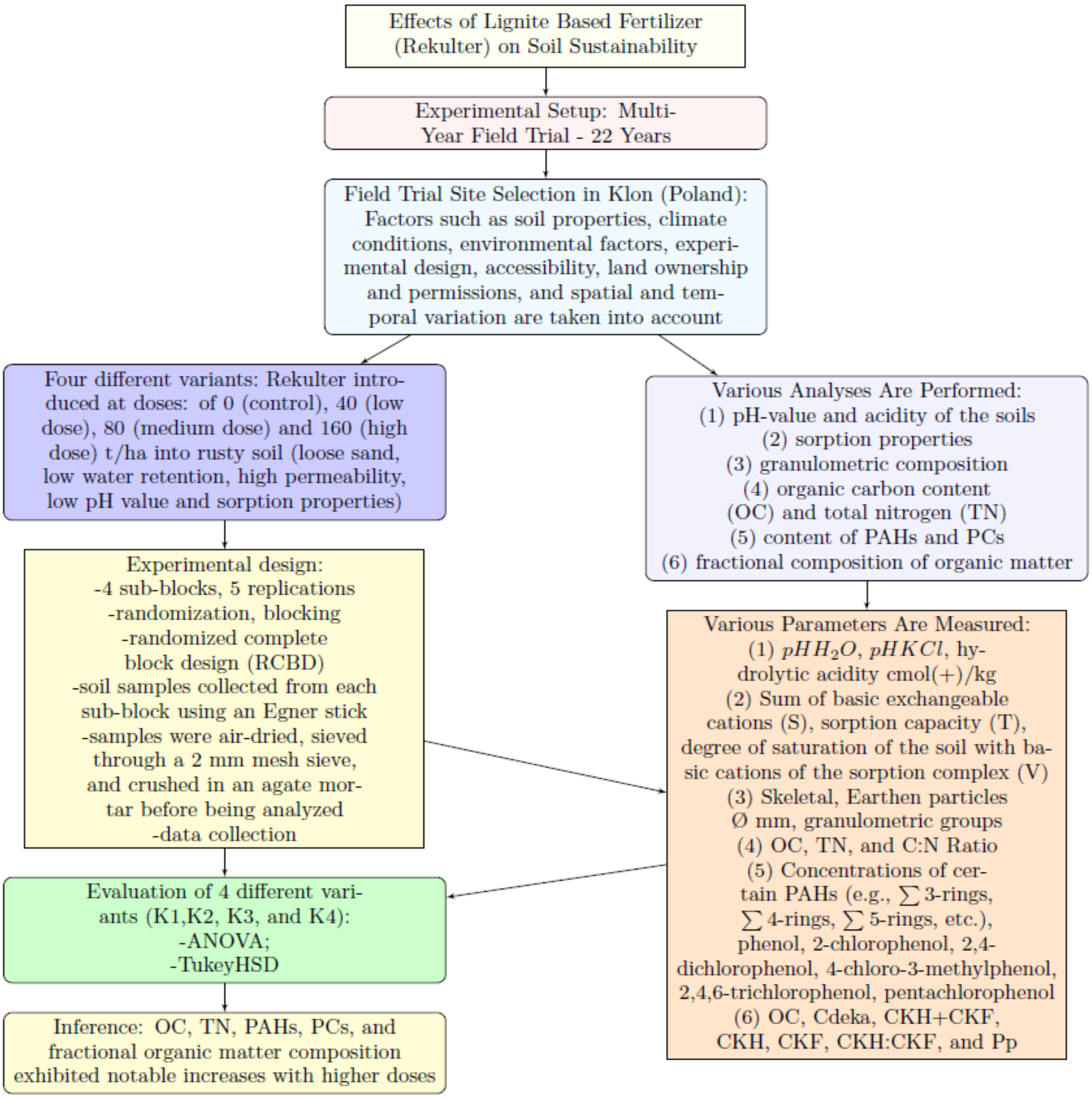

Figure 3. Schematic diagram of the experimental multi-year field trial; source: own elaboration.

2.2.2. Evaluation of Different Parameters' Measures

In this study, the Analysis of Variance (ANOVA) method serves as a central tool to evaluate the significance of the differences observed among several experimental treatments. ANOVA is strategically applied to evaluate different parameters, including soil pH, acidity, granulometric composition, soil fertility, nutrient content (organic carbon and total nitrogen), contaminants such as PAHs and PCs, and fractional composition of organic matter. Data analysis was performed with R-Studio statistical software (version 2023.03.0-daily+82.pro2), using specific packages for different stages of analysis. The *car* package facilitated ANOVA calculations, the *agricolae* package allowed Tukey's honestly significant difference (HSD) test following ANOVA, and the *emmeans* package allowed flexible post hoc comparisons and mean separations. ANOVA was used to assess the overall significance of reclamation (Rekulter) treatments on soil properties, while Tukey's HSD test was used for post hoc pairwise comparisons to detect specific differences between treatment groups. The ANOVA model used in the analysis can be represented as:

$$Y_{ijkl} = \mu + \tau_k + \beta_j + (\tau\beta)_{kj} + \gamma_i + (\tau\gamma)_{ik} + (\beta\gamma)_{ij} + \epsilon_{ijkl} \quad (1)$$

where

- Y_{ijkl} represents the observed value of the soil property for the l-th replicate in the i-th year, in the j-th subfield, and in the k-th treatment group (Rekulter treatment variant),
- μ is the overall mean of the soil property across all treatment groups,
- τ_k represents the fixed effect of the k-th Rekulter treatment variant,
- β_j represents the fixed effect of the j-th subfield,
- $\tau\beta_{kj}$ represents the interaction effect between Rekulter treatment variant k and subfield j,
- γ_i represents the fixed effect of the i-th year,
- $\tau\gamma_{ik}$ represents the interaction effect between Rekulter treatment variant k and year i,
- $\beta\gamma_{ij}$ represents the interaction effect between subfield j and year i, and
- ϵ_{ijkl} is the random error term.

The study rigorously adhered to the ANOVA assumptions of normal data distribution and homogeneity of variance through careful experimental design, including appropriate replication per treatment (5 replications were performed), randomization, and blocking procedures (200 samples were collected in each year of the study, 50 for each Rekulter treatment). This approach ensured effective control of potential sources of variability and validated the basic assumptions necessary for ANOVA analysis. The null hypothesis tested by ANOVA is that there is no significant difference in the mean soil property values among the different Rekulter treatments. Tukey's HSD test is then performed to identify specific treatment groups that show significant differences. This test allows for careful pairwise comparisons between experimental treatment doses, providing nuanced insights into specific dose-dependent effects of Rekulter. HSD is calculated as follows:

$$\text{HSD} = q \cdot \sqrt{\left(\frac{\text{MSW}}{n}\right) \cdot \left(\frac{1}{a}\right)} \quad (2)$$

where

- HSD is the Honestly Significant Difference,
- q is the critical value from the Studentized Range Distribution table,
- MSW is the Mean Square Within (error variance),
- n is the total number of observations,
- a is the number of groups being compared.

Combining multiple replicates in ANOVA and Tukey's HSD tests provides a comprehensive assessment of dose-dependent effects on soil properties. This approach enhances statistical power by increasing sample size and facilitates a nuanced understanding of treatment responses across the dose range. The combination of ANOVA and Tukey's HSD tests provides a robust framework for analyzing and interpreting Rekulter treatment effects on soil properties, allowing for informed decision-making and meaningful conclusions from study data. The methodological significance of Tukey's HSD lies in its ability to identify statistically significant differences between experimental groups, specifically addressing the multiplicity problem arising from multiple pairwise comparisons [45,46]. For example, Newman [45] addresses the multiplicity problem by discussing ranking with multiple types of pairwise comparisons, which is relevant to the challenges associated with multiple comparisons and statistical corrections. Similarly, Midway et al. [46] provide practical guidance on how to choose the best multiple comparisons test while imposing strict control over Type I errors [47]. Thus, the use of ANOVA and Tukey's HSD together strengthens the statistical underpinning of the study and allows for careful dissection of the relationships between Rekulter doses and various soil parameters.

Numerous parameters (i.e., $p_1, p_2, p_3, \ldots, p_k$) are measured for each Rekulter treatment. In addition, combining parameters within categories streamlines statistical analysis, increasing efficiency and practicality. Parameters such as OC and TN, or contaminants such as PAHs and PCs, often represent interrelated aspects of soil properties. Analyzing them together captures synergistic effects and complex interactions, providing a more holistic understanding of the soil system. For example, analysis of OC and TN can provide insights into soil health and nutrient cycling, reflecting their synergistic effects and importance for soil fertility and productivity [48–52]. Similarly, combined analysis of PAHs and PCs helps to comprehensively assess pollution levels and sources [45,46]. Such integrated approaches maximize statistical power and facilitate deeper insights into treatment effects on soil dynamics and properties [53,54]. The *F*-statistic is calculated to determine if there is a significant difference in the means of the measured parameters between the treatments. Whenever the null hypotheses are rejected, then post hoc tests (i.e., Tukey's HSD tests) are performed to determine which specific means are significantly different from each other. It is important to note that ANOVA and Tukey's HSD tests are commonly used in agricultural and environmental studies to compare the means of multiple treatment groups. Several scientific articles support the use of ANOVA or Tukey's HSD methods in agricultural and environmental research to analyze the effects of different treatments on soil properties and plant growth. For example, Arafat et al. [55] discuss the use of ANOVA and Tukey's HSD analysis to differentiate between rice and maize. Salisu et al. [56] discuss the use of ANOVA in agricultural research to compare the effectiveness of different types of fertilizers, crop varieties, or farming practices. In turn, Bello and Bradford [57] used ANOVA and Tukey's HSD to compare the physical characteristics of Brassica seeds and their impact on germination performance and plant blindness. They assessed multiple seed parameters, such as weight, length, width, thickness, and density, and subjected these measurements to statistical analyses using ANOVA to identify any significant variations across different seed lots. Subsequently, Tukey's HSD was applied to pinpoint specific pairwise comparisons with significance. Furthermore, while ANOVA and Tukey's HSD tests are preferred for their efficiency in handling multiple treatment groups and pairwise comparisons, it is important to recognize alternative statistical methods. Simple *t*-tests or nonparametric tests such as Kruskal–Wallis or Mann–Whitney U tests, while robust in certain scenarios, may lack the ability to efficiently handle multiple comparisons and provide estimates of effect sizes and confidence intervals, limiting interpretation and decision-making [58,59]. Compared to these methods, ANOVA and Tukey's HSD offer several advantages, including simultaneous comparison of means across multiple groups, robustness to violations of assumptions, and estimates of variance components [60,61]. Overall, this study's rigorous statistical methodology, combining ANOVA and Tukey's HSD, ensures a comprehensive analysis and interpretation of Rekulter treatment effects on soil properties and contributes to the scientific discourse on sustainable agricultural practices.

3. Results

3.1. Physicochemical Properties of Soils

3.1.1. pH Value and Acidity of the Soils

The application of Rekulter led to an increase in pH measured in water and in 1 M KCl, and a decrease in hydrolytic acidity, as the Rekulter dose increased (see Table 1). This consistent pattern suggests that higher Rekulter doses are associated with higher pH and lower hydrolytic acidity, indicating a neutralizing effect on soil acidity.

These results align with the intended purpose of Rekulter to improve soil properties and reduce contaminant bioavailability by altering soil pH and acidity. However, it is important to note that the data did not yield statistically significant results to support the hypothesis that Rekulter application has a positive effect on soil pH and acidity, as indicated by the ANOVA results for different experimental variants (F-value = 0.02 with corresponding p-value > 0.05; see Table A1 in Appendix A).

Table 1. Reaction and acidity of the fallow soil.

Dose (Symbol)	pH_{H2O} (SE)	pH_{KCl} (SE)	Hydrolytic Acidity cmol(+). kg^{-1} (SE)
Control (K1)	4.90 (0.0071)	3.76 (0.0042)	5.80 (0.0141)
Low (K2)	5.10 (0.0057)	4.10 (0.0028)	4.08 (0.0113)
Medium (K3)	5.66 (0.0042)	5.35 (0.0057)	2.90 (0.0085)
High (K4)	6.75 (0.0085)	6.05 (0.0071)	0.93 (0.0057)

Source: own elaboration; Note: SEs represent the standard errors associated with their respective parameters' means.

3.1.2. Sorption Properties of Soils

Table 2 presents data on the sum of basic exchangeable cations (S), sorption capacity (T), and the degree of saturation of the soil with basic cations of the sorption complex (V) for different field trial variants (K1, K2, K3, and K4) of Rekulter application.

Table 2. Sum of basic exchangeable cations (S), sorption capacity (T), and degree of saturation of the soil with basic cations of the sorption complex (V).

Dose (Symbol)	S (cmol(+). kg^{-1}) (SE)	T cmol(+). kg^{-1} (SE)	V (%) (SE)
Control (K1)	3.6 (0.097)	9.4 (0.211)	37 (0.849)
Low (K2)	5.7 (0.118)	9.8 (0.219)	62 (0.992)
Medium (K3)	11.8 (0.101)	14.7 (0.202)	80 (0.849)
High (K4)	13.2 (0.131)	14.1 (0.221)	93 (1.131)

Source: own elaboration; Note: SEs represent the standard errors associated with their respective parameters' means.

These results indicate that the ability of the soil to retain and exchange basic cations increases with the application of Rekulter at higher doses, as shown by the increase in S and T values from K1 to K4. The degree of saturation of the soil with basic cations of the sorption complex (V) also increases with higher doses of Rekulter, indicating that a higher proportion of the soil sorption sites are occupied by basic cations. These results suggest that Rekulter application leads to an improved ability of the soil to bind and exchange cations, which may have significant implications for nutrient availability and plant growth. The observed trends are consistent with the intended effects of Rekulter on soil properties and nutrient dynamics, highlighting its potential role in soil improvement and fertility enhancement. However, similar to the soil pH and acidity measurements, the data did not provide statistically significant results to support the hypothesis that Rekulter application (at different rates) results in different sorption properties of soils, as indicated by the ANOVA results (F-value = 2.24, p-value > 0.05; see Table A2 in Appendix A). Therefore, although the data show a consistent pattern, they do not provide conclusive evidence to support the hypothesis of significant differences in sorption properties of soils among different doses of Rekulter.

3.1.3. Granulometric Composition of Soils

The application of a restorative agricultural dose of Rekulter (160 t/ha) resulted in a transformation of the granulometric composition of the soil, shifting from loose sand to weakly developed loamy sand, as shown by the data presented in Table 3. The values presented in Table 3 reflect the proportion of distinct soil particle sizes, represented as percentage fractions.

Table 3. Granulometric composition of the soil.

Dose (Symbol)	**Fractional Content %**				**Granulometric Groups**
	Skeletal Particles (SE)	**Earthen Particles Ø mm**			
		Sand1-0.1 (SE)	**Silt0.1-0.02 (SE)**	**Floatable Particles < 0.02 (SE)**	
Control (K1)	1.48 (0.0035)	89.5 (0.034)	6.0 (0.0023)	4.5 (0.002)	loose sand
Low (K2)	1.49 (0.0037)	89.8 (0.035)	6.0 (0.0026)	4.2 (0.0022)	loose sand
Medium (K3)	1.50 (0.004)	89.7 (0.037)	6.0 (0.0024)	4.3 (0.0023)	loose sand
High (K4)	1.53 (0.0042)	88.5 (0.03)	6.0 (0.0027)	5.5 (0.0029)	weak loamy sand

Source: own elaboration; Note: SEs represent the standard errors associated with their respective parameters' means.

Notably, the skeletal component—which may encompass larger elements like gravel or coarse materials—contributes to the structural integrity of the soil. Across all experimental treatments, the skeletal component exhibits a relatively diminished presence, signifying the absence of coarse fragments as the primary soil constituent. Within Table 3, three columns delineate distinct size fractions of earthen particles (Ø mm), encompassing sand (1-0.1 mm), silt (0.1-0.02 mm), and floatable particles (<0.02 mm). Evidently, a diminishing trend in the proportion of these particles is observed as the analysis progresses from sand to finer fractions. The predominant fraction is identified as sand, while silt and floatable particles are minor constituents. The final column provides descriptive terminology for the granulometric composition, such as "loose sand" and "weak loamy sand", to facilitate the classification of soils based on their predominant particle size and consistency. The data provide compelling evidence of variations in granulometric composition due to the different experimental conditions, particularly the application of different Rekulter doses. The specific classification of granulometric groups (e.g., "loose sand" or "weak loamy sand") provides information on the physical properties and structure of the soil under different treatments. These results may have implications for the water retention, drainage, aeration, and nutrient availability of the soil. The differences in granulometric composition may contribute to differences in soil properties and potentially affect plant growth and nutrient uptake under each experimental condition. However, it should be noted that the data did not provide statistically significant results to support the hypothesis that different doses of Rekulter induce statistically significant changes in the granulometric composition of the soil, as indicated by the ANOVA results (F-value = 0.05 and p-value > 0.05; see Table A3 in Appendix A). Therefore, although the data show a consistent pattern, they do not provide conclusive evidence to support the hypothesis of significant differences in granulometric composition of soils among different doses of Rekulter.

3.1.4. Soil Fertility and Nutrient Content

Table A4 in Appendix A shows significant results for soil OC and TN levels and their respective C:N ratios under various experimental settings. This table presents data collected over several years and under different Rekulter dosage conditions. In addition, Figure 4 illustrates a comparison of OC levels between different Rekulter treatments.

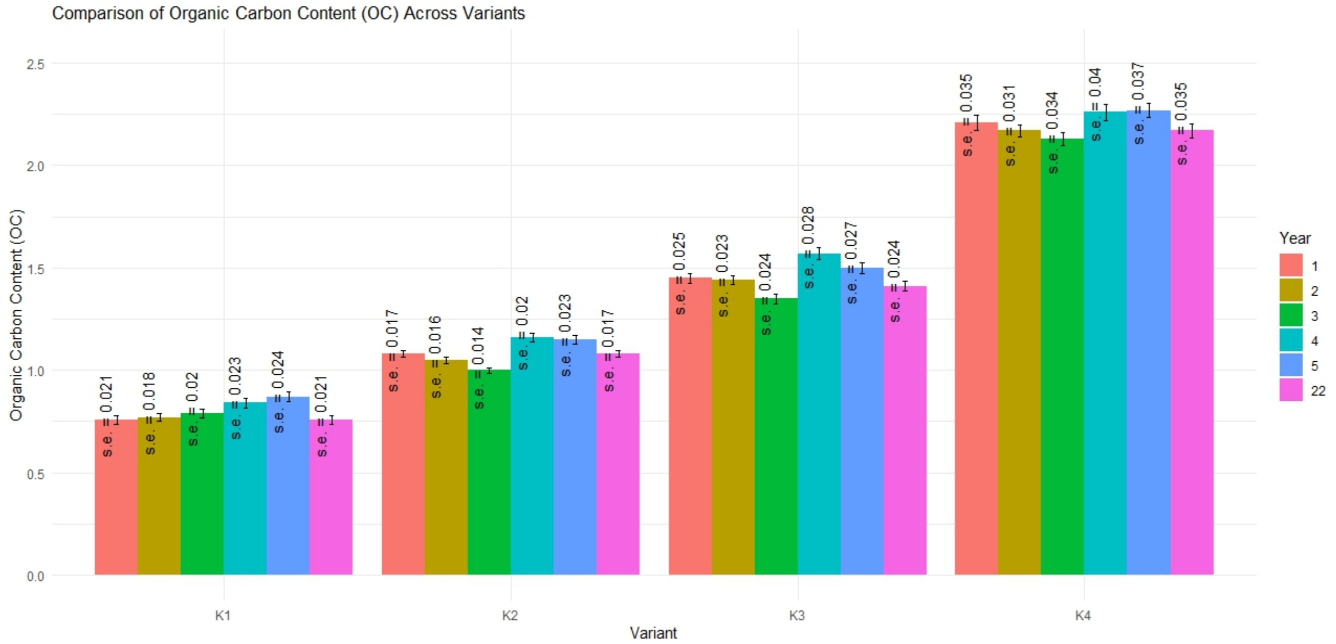

Figure 4. Comparison of organic carbon (OC) across various Rekulter doses; source own elaboration; Note: s.e. values correspond to the standard errors of the respective OC measurements.

When OC levels are examined, a direct correlation between Rekulter dose and OC content is observed, indicating that higher Rekulter doses result in increased OC levels. In all experimental treatments (K1, K2, K3, and K4), there is a consistent increase in OC levels in the 3rd and 4th year. However, in the last year of the multi-year field study, the OC content shows a decrease compared to the levels observed in years 4 and 5.

Figure 5 illustrates the comparison of TN levels under different Rekulter treatments.

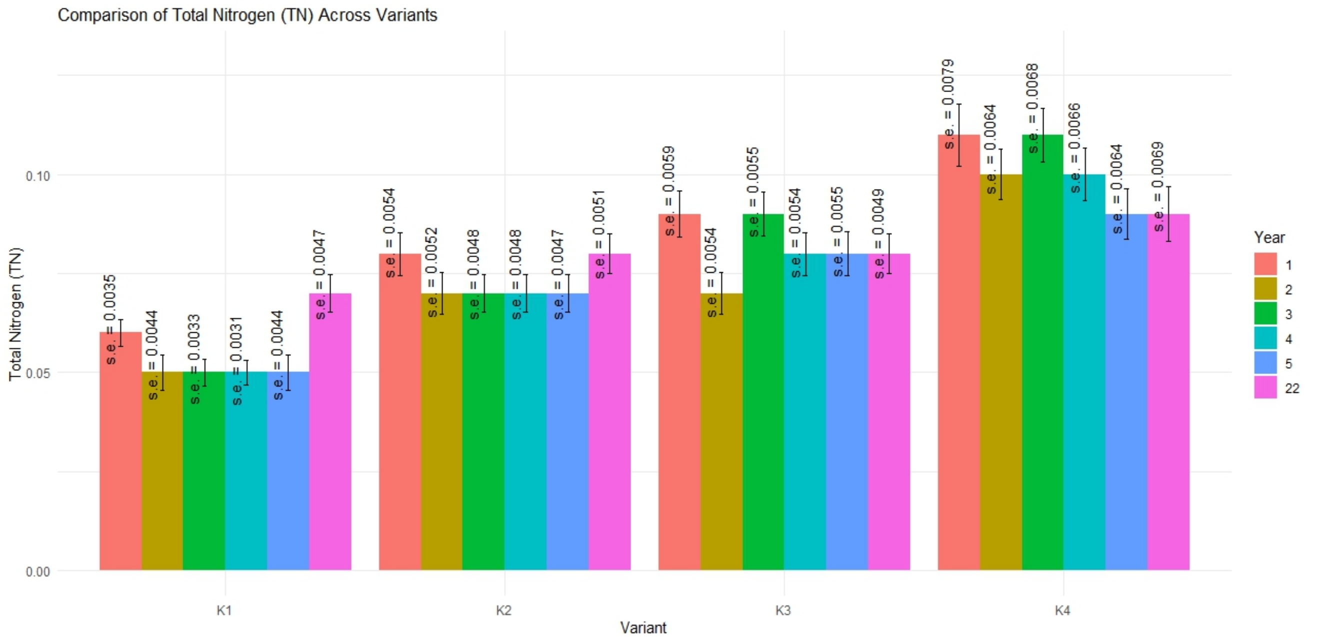

Figure 5. Comparison of total nitrogen (TN) across different Rekulter doses; source own elaboration; Note: s.e. values correspond to the standard errors of the respective TN measurements.

Contrasting patterns emerge in the analysis of total nitrogen (TN). The control and low Rekulter doses show significantly higher TN levels in the last year of the trial. In contrast, the medium and high Rekulter doses show a significant decrease in TN levels in the last year compared to the early years of the trial.

The variations in OC during the multi-year field trial can be attributed to the fertilization and fallow treatments applied. The changes in OC and TN over time indicate that the application of Rekulter may have positively influenced the accumulation of organic matter and nitrogen in the soil. In addition, trends in C:N ratios (as shown in Table A4 in Appendix A) may reflect changes in organic matter decomposition and stability. The changes in C:N ratios also highlight the dynamic nature of organic matter transformation. These results have implications for soil fertility, nutrient cycling, and carbon sequestration potential. The patterns observed can help researchers understand how different treatments affect soil organic carbon (SOC) and nitrogen dynamics, and provide valuable information for soil management and sustainable agricultural practices.

In terms of soil management, the incorporation of Rekulter caused a modest shift in TN levels. However, this change was minimal compared to the variability observed in OC, which resulted in a notable rise in the carbon to nitrogen (C:N) ratio corresponding to the increasing doses of Rekulter application (as shown in Table A4 in Appendix A). This phenomenon is due to the incorporation of organic material into the soil that has a broad spectrum of C:N ratios, with the entire TN reservoir associated with recalcitrant organic compounds that are resistant to mineralization. The highest C:N ratio (24:1) was observed at the site with the highest Rekulter dose (see Table A4 in Appendix A). This finding has important implications for sustainable agricultural practices. To ensure optimal nitrogen management, which is a fundamental criterion in sustainable agriculture, mineral nitrogen fertilization should be applied in addition to lignite to enrich soils with organic matter.

Tables A5 and A6 in Appendix A present the ANOVA and Tukey's HSD results corresponding to the OC and TN (in %) in the soil. The ANOVA results (F value = 10.27104, $p < 0.05$) reject the null hypothesis, indicating that there are significant differences among the treatments (different doses of Rekulter) in terms of OC, TN, and C:N ratio. The Tukey's HSD results further support the rejection of the null hypothesis by revealing significant differences between certain pairs or treatments (e.g., K4-K1, K4-K2, and K4-K3), indicating that specific doses of Rekulter result in different soil composition outcomes (as shown in Figure 6).

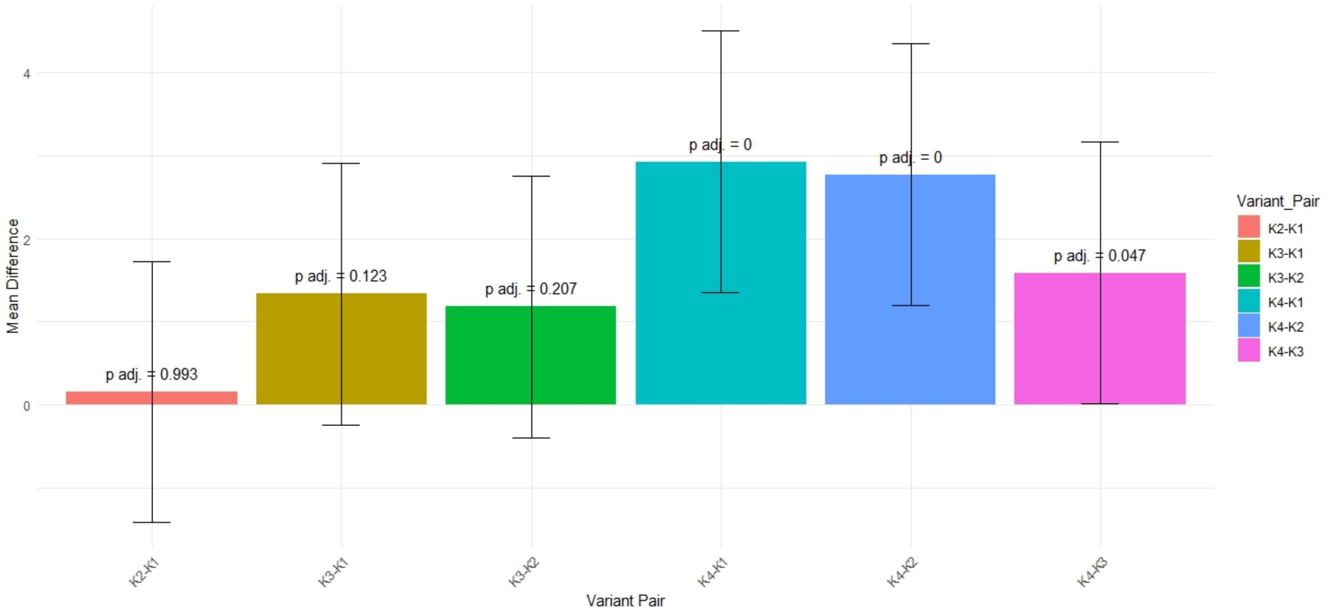

Figure 6. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the levels of organic carbon (OC) and total nitrogen (TN); source: own elaboration.

Given the statistically significant results of both ANOVA and Tukey's HSD, the hypothesis of significant differences in PAH and PC levels in soil among different doses of Rekulter is supported. The results reveal a distinct influence of varying Rekulter dosages on soil characteristics, as indicated by robust statistical evidence. Particularly, the highest applied dose (designated K4) exhibits notable disparities when contrasted with lower doses, highlighting the significance of dosage in modulating SOC, TN, and the C:N ratio (as shown Table A4 in Appendix A).

This observation supports a dose-dependent response to Rekulter application, thereby substantiating the hypothesis of significant differences in SOC, TN, and the C:N ratio levels in soil among different doses of Rekulter. The lack of statistical significance for K2-K1, K3-K1, and K3-K2 suggests that there might be a threshold or critical mass of Rekulter application needed to observe a significant impact on soil composition (i.e., threshold effect). Below a certain dosage (represented by K2 and K3), the differences may not be discernible. The significant differences for K4, the treatment with the highest dose (160 t/ha), compared to K1, K2, and K3, indicate a dose-dependent response. Higher doses of Rekulter lead to more pronounced changes in SOC, TN, and C:N ratio. The results suggest that for Rekulter to exert a statistically significant impact on soil quality, especially in terms of OC, TN, and C:N ratio, a dosage above a certain threshold (represented by K4) is crucial. This finding is relevant for farmers and practitioners, as it provides insights into optimizing Rekulter application for enhanced soil quality.

3.1.5. Content of PAHs and PCs

Soil PAH and PC concentration data for different experimental treatments are presented in Table 4.

Table 4. Contents of PAHs and PCs in soil (μg/kg).

Dose (Symbol)	∑3-Rings		∑4-Rings		∑5-Rings		∑6-Rings		∑17 PAHs	
	PY (SE)	**LY (SE)**	**PY (SE)**	**LY (SE)**	**PY (SE)**	**LY (SE)**	**PY (SE)**	**LY (SE)**	**PY (SE)**	**LY (SE)**
Control (K1)	42 (2.12)	35 (2.47)	186 (4.39)	74 (2.93)	122 (3.55)	46 (2.37)	58 (1.84)	32 (1.56)	408 (9.61)	187 (5.38)
Low (K2)	29 (1.98)	-	67 (1.70)	-	57 (1.41)	-	33 (1.27)	-	186 (4.52)	-
Medium (K3)	16 (1.13)	-	37 (0.99)	-	36 (1.11)	-	23 (0.71)	-	112 (3.82)	-
High (K4)	21 (1.84)	34 (2.14)	62 (1.70)	47 (2.40)	53 (1.56)	40 (2.26)	31 (1.41)	28 (1.84)	167 (3.11)	149 (3.39)

Dose (Symbol)	phenol (SE)	2-chlorophenol (SE)	2,4-dichloro phenol (SE)	4-chloro-3-methyl phenol (SE)	2,4,6-trichloro phenol (SE)	penta chloro phenol (SE)
Control (K1)	14 (1.97)	<0.1 -	<0.1 -	<0.2 -	<0.2 -	<1.0 -
Low (K2)	19 (2.69)	<0.1 -	<0.1 -	<0.2 -	<0.2 -	<1.0 -
Medium (K3)	70 (9.76)	<0.1 -	<0.1 -	<0.2 -	<0.2 -	<1.0 -
High (K4)	76 (10.74)	<0.1 -	<0.1 -	<0.2 -	<0.2 -	<1.0 -

Source: own elaboration; Note: PY—penultimate year of the multi-year trial; LY—last year of the multi-year trial. SEs represent the standard errors associated with their respective parameters' means.

The data indicate the presence of different PAHs with different ring numbers (3, 4, 5, and 6) in the soil. There is variability in soil PAH levels for different years and treatments. In particular, the concentrations of certain PAHs (e.g., ∑3-rings and ∑4-rings) appear to have decreased for some treatments between the penultimate and final year of the multi-year field study, while others remained relatively stable. In addition, Table 4 shows the levels of specific PCs in the soil. PCs are of interest because of their potential influence on soil health and microbial activity. The data show the presence of several PCs (e.g., phenol and 2-chlorophenol) in the soil, generally at low concentrations, as many compounds are reported at levels "<0.1" or "<0.2".

Concentrations of PAHs and PCs appear to vary between the different treatments. For some doses, PAH concentrations fluctuate between the penultimate year and the final year of the multi-year study, while others remain relatively stable. The variation in concentrations observed between different treatments and between different years can be attributed to several factors, including experimental conditions, soil properties, and microbial activity. The low concentrations of PCs suggest that the soil is not significantly affected by these compounds in the context studied. However, it is important to remember that even low levels of certain compounds may have ecological consequences. Further analysis and correlation with other soil parameters could help researchers better understand the effects of concentrations of these compounds on soil health and ecosystem dynamics.

Results of ANOVA and Tukey's HSD for PAHs and PCs in soil are shown in Tables A7 and A8 in Appendix A. The ANOVA for PAHs and PCs in soil shows statistically significant differences between different treatments (F value = 5.562676, p-value < 0.05; see Table A7 in Appendix A). In addition, the Tukey's HSD results show specific pairs of treatments with significant differences, revealing nuances in the effects of Rekulter on soil contamination. In the context of Rekulter applications, the study provides evidence that even at the minimum dose, there are significant differences in soil contamination compared to untreated controls. Specifically, no statistically significant differences were observed when the dose was incrementally increased from K2 to K3, K3 to K4, or K2 to K4. These observations suggest a potential threshold effect whereby further increases in Rekulter dose may not significantly affect soil contamination levels within the range tested. It is important to note that K4, the highest dose (160 t/ha), does not show significantly different contamination levels compared to K2 or K3 (as shown in Figure 7). This may indicate the presence of a critical mass or efficacy plateau, highlighting the importance of optimizing the application of Rekulter for both environmental and economic considerations.

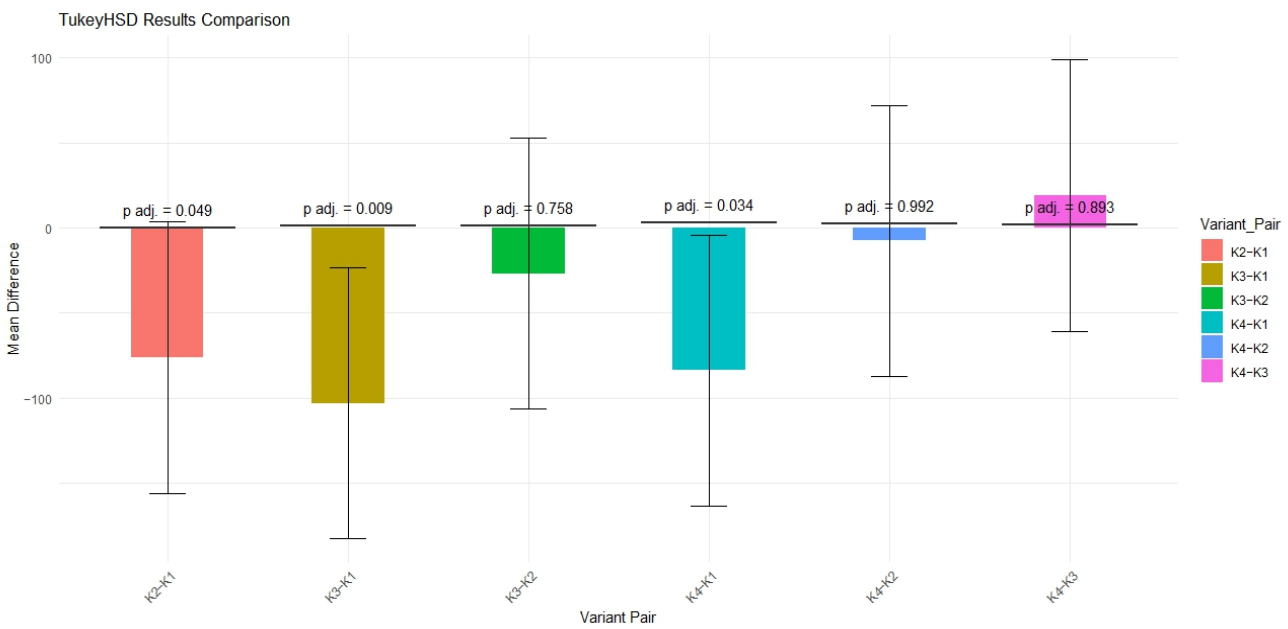

Figure 7. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the PAHs and PCs content; source: own elaboration.

The ANOVA results support the rejection of the null hypothesis, indicating overall significant differences between the treatments (p-value = 0.009057). More specifically, Tukey's HSD shows that only comparisons with the control treatment (K1) exhibit significant differences, while comparisons between higher doses do not. This is consistent with the interpretation that above a certain dose, the addition of Rekulter does not significantly affect soil contamination. The null hypothesis is rejected for certain pairwise comparisons (e.g., K2-K1, K3-K1, and K4-K1), supporting the notion that any application of Rekulter results in significant changes compared to no application, but increasing the dose may not result in further significant improvements. These results provide valuable guidance for optimizing Rekulter application in agriculture, and emphasize the need for a balanced approach that considers both soil improvement and potential environmental impacts.

3.2. Fractional Composition of Organic Matter

The results of the fractional composition of organic matter determined by the Tyurin method are detailed in Tables 5 and 6. The Tyurin technique allowed the isolation and quantification of the following humic matter fractions: (1) easily mobile SH species, solubilized after extraction with 0.5 M H_2SO_4; (2) forms of SH complexed with calcium and mobile forms of R_2O_3, separated from an alkaline extract at 0.1 M NaOH concentration, further separated into humic and fulvic acids; (3) strongly bound SH components associated with the mineral portion of the soil, obtained by a hot extract using a mixture of 0.1 M/0.02 M NaOH, also yielding humic and fulvic acid fractions; and (4) residual humic substances derived from the extraction process.

Table 5. Fractional composition of organic matter (in g/kg of soil).

Dose (Symbol)	OC (SE)	Cdeka (SE)	Extraction with 0.1 M NaOH after Decalcification			Heat-Treated Extraction with 0.02 M NaOH			Sum of Fractions		
			CKH + CKF (SE)	CKH (SE)	CKF (SE)	CKH + CKF (SE)	CKH (SE)	CKF (SE)	CKH + CKF (SE)	CKH (SE)	CKF (SE)
Control (K1)	7.6 (0.283)	0.83 (0.014)	2.92 -	1.55 (0.511)	1.37 (0.281)	2.81 -	1.71 (0.294)	1.10 (0.162)	5.73 -	3.26 (0.294)	2.47 (0.162)
Low (K2)	10.8 (0.324)	1.08 (0.018)	3.43 -	2.44 (0.446)	0.99 (0.216)	2.93 -	2.12 (0.257)	0.81 (0.141)	6.36 -	4.56 (0.257)	1.80 (0.141)
Medium (K3)	14.1 (0.373)	0.55 (0.022)	5.55 -	4.47 (0.674)	1.08 (0.191)	4.50 -	3.39 (0.388)	1.11 (0.214)	8.94 -	7.86 (0.388)	2.19 (0.214)
High (K4)	21.7 (0.483)	0.80 (0.027)	7.42 -	6.51 (0.884)	0.91 (0.217)	5.85 -	4.95 (0.508)	0.90 (0.113)	13.27 -	11.46 (0.508)	1.81 (0.280)

Source: own elaboration; Note: SEs represent the standard errors associated with their respective parameters' means.

Table 6. Fractional composition of organic matter (in % OC).

Dose (Symbol)	Cdeka (SE)	Extraction with 0.1 M NaOH				Heat-Treated Extraction with 0.02 M NaOH				Sum of Fractions				Pp (SE)
		CKH + CKF (SE)	CKH (SE)	CKF (SE)	CKH:CKF (SE)	CKH +CKF (SE)	CKH (SE)	CKF (SE)	CKH :CKF (SE)	CKH +CKF (SE)	CKH (SE)	CKF (SE)	CKH :CKF (SE)	
Control (K1)	10.9 (1.346)	38.4 -	20.4 (2.22)	18.0 (2.09)	1.13 -	37.0 -	22.5 (2.46)	14.5 (1.56)	1.55 -	75.4 -	42.9 (3.98)	32.5 (3.03)	1.32 -	24.6 (3.07)
Low (K2)	10.0 (1.129)	31.8 -	22.6 (2.53)	9.2 (1.15)	2.46 -	27.1 -	19.6 (2.07)	7.5 (0.88)	2.61 -	58.9 -	42.2 (4.45)	16.7 (2.03)	2.53 -	41.1 (4.56)
Medium (K3)	3.9 (0.407)	39.4 -	31.7 (3.26)	7.7 (0.93)	4.12 -	31.7 -	24.0 (2.67)	7.9 (0.94)	3.04 -	71.3 -	55.7 (6.07)	15.6 (2.14)	3.57 -	28.7 (3.43)
High (K4)	3.7 (0.421)	34.2 -	30.0 (3.67)	4.2 (0.59)	7.14 -	27.0 -	22.8 (2.48)	4.2 (0.53)	5.43 -	61.2 -	52.8 (5.46)	8.4 (0.97)	6.29 -	47.2 (5.12)

Source: own elaboration; Note: SEs represent the standard errors associated with their respective parameters' means.

The addition of Rekulter to the soil resulted in an increase in the SOC (as shown in Table 5, in g/kg, and Table 6, as a percentage), but this was mainly associated with an increase in the humic acid content. Soils to which Rekulter was added were characterized by a higher content of the humic acid fraction and a lower (or similar) content of the fulvic acid fraction compared to the control treatment. This was true for all forms of humic matter and for all experiments. More importantly, it suggests that the application of carbon has a relatively permanent character that can be observed many years after its introduction into the soil. The results presented in Table 6 (fractional composition in % OC) allow the evaluation of the quality of the organic matter. The soils to which Rekulter was added were characterized by a higher proportion of the humic acid fraction (CKH) and a lower proportion of the fulvic acid fraction (CKF) than the soils of the control variants, which is very favorable from the point of view of evaluating the quality of SOM. Consequently, the introduction of lignite into the soil leads to higher values of the CKH:CKF ratio. This effect is still observed many years after the introduction of lignite into the soil.

Tables 5 and 6 provide insight into the fractional composition of SOM for different treatments of the field trial. The data show the fractional composition of the organic matter with respect to different components such as Cdeka, extraction with NaOH, and heat-treated extraction. In particular, the OC fraction is the largest component of the organic matter. It varies from about 7.6 g/kg to 21.7 g/kg for the different treatments. This variation could be due to factors such as original soil composition, vegetation cover, and management practices. The other fractions, such as "extraction with 0.1 M NaOH after decalcification" and "heat-treated extraction with 0.02 M NaOH", show variation among the different treatments. These fractions represent different forms of organic matter, including labile and recalcitrant fractions. The CKH + CKF fraction is the sum of Cdeka, CKH, and CKF, which represent different components of organic matter with different degrees of decomposition.

The ANOVA results for both fractional organic matter composition results (in g/kg soil and in % OC) indicate that there are indeed significant differences between the experimental treatments (in this respect, the hypothesis of significant differences in fractional organic matter composition among different doses of Rekulter is supported). In addition, the Tukey's HSD post hoc tests show that certain pairwise comparisons are statistically significant. Tables A9 and A10 in Appendix A show the results of the ANOVA on the fractional composition of organic matter (in g/kg soil). The significant differences in the K4-K1 and K4-K2 pairs indicate that the highest Rekulter dose (K4) induces unique changes in the absolute fractional composition of organic matter. This supports the hypothesis of significant differences in fractional organic matter composition between treatments and highlights the dose-dependent effect of Rekulter.

The fractional composition of the organic matter shows variations depending on the experimental conditions. In particular, the CKH + CKF and CKH:CKF fractions indicate different degrees of decomposition and stabilization of organic matter under different conditions. The variations in these fractions indicate differences in the decomposition and transformation of organic matter. Overall, the fractional composition of SOM is influenced by a combination of factors, including initial soil properties, crop inputs, microbial activity, and management practices. The variation observed among cultivars and years demonstrates the dynamic nature of SOM and its response to changing environmental conditions. The presence of different organic matter fractions, such as labile and recalcitrant forms, illustrates the complexity of SOM and its potential contribution to nutrient cycling, carbon sequestration, and overall soil fertility. Further studies and analyses are essential to further explore the specific factors that lead to the observed variations in organic matter composition and to better understand the role of these fractions in soil health and ecosystem functions.

The ANOVA and Tukey's HSD corresponding to the fractional composition of organic matter (in % OC) are shown in Tables A11 and A12 in Appendix A. The ANOVA results (as shown in Table A11 in Appendix A) indicate that there are significant differences between the experimental treatments. In addition, the Tukey's HSD post hoc tests show that certain pairwise comparisons are statistically significant. Specifically, the significant differences in the K2-K1 and K4-K1 pairs emphasize that, proportionally, the highest Rekulter dose (K4) results in significant shifts in composition. This is consistent with the hypothesis of significant differences in organic matter composition among different doses of Rekulter.

The observed patterns suggest nuanced dynamics in soil organic matter composition at different Rekulter doses. For Table A10 in Appendix A, the significant differences in K4-K1 and K4-K2 imply that higher Rekulter doses uniquely contribute to the change in fractional composition in absolute terms (g/kg soil). This is consistent with the idea that beyond a certain threshold, Rekulter doses can induce significant changes (see Figure 8).

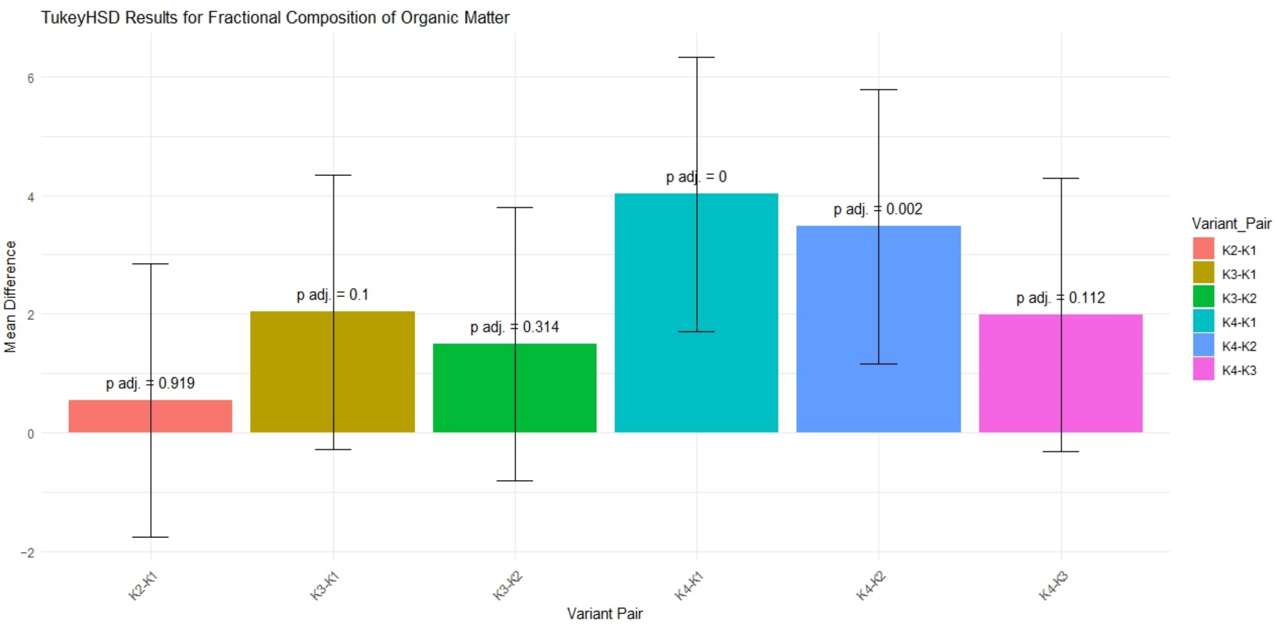

Figure 8. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the fractional composition of organic matter (in g/kg of soil); source: own elaboration.

The percentage-based perspective supports this notion with significant differences in the K2-K1 and K4-K1 pairs (as shown in Table A12 in Appendix A and in Figure 9). This implies that, proportionally, K4 induces significant shifts in composition, highlighting the effect of Rekulter on the relative distribution of organic matter constituents (see Figure 9). Taken together, these results suggest a dose-dependent influence on SOM composition.

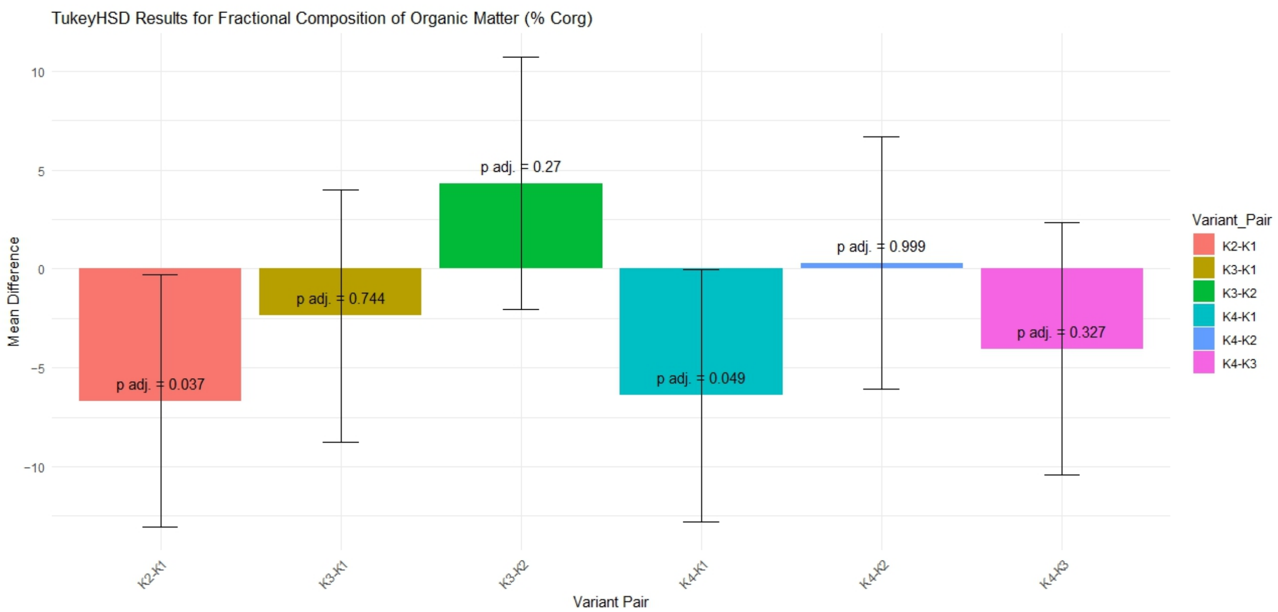

Figure 9. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the fractional composition of organic matter (in % OC); source: own elaboration.

From an agricultural perspective, understanding how different Rekulter doses affect fractional composition provides valuable insight into soil health and nutrient availability. The significant differences observed highlight the need for precision in Rekulter application to effectively optimize soil composition. This nuanced approach is consistent with sustainable agricultural practices that emphasize not only the presence of Rekulter, but also the specific doses that produce optimal results.

Overall, the observed statistically significant differences in certain pairs support the hypothesis that Rekulter doses play a critical role in shaping soil fractional organic matter composition.

4. Discussion

In this study, the effects of the Rekulter treatments on various soil parameters were thoroughly examined. Key factors evaluated included pH, soil acidity, sorption properties, granulometric composition, OC, and TN levels, as well as PAH and PC concentrations and organic matter fractional composition. The study results shed light on the complex relationship between soil response and Rekulter application by integrating these findings with existing scientific knowledge [18]. It is important to note that Rekulter, an organic-mineral additive derived from lignite, is characterized by its ability to improve the physical, chemical, and biological properties of soils while reducing the bioavailability of contaminants [18]. Consisting of lignite, lowland peat, lignite ash, and mineral fertilizer, Rekulter has been successfully used in agricultural practices alongside other low-rank, coal-based fertilizers [7]. In particular, its use has shown positive results in improving plant availability of zinc, lead, and cadmium, in addition to serving as a source of humic matter for soil improvement [7].

The results of this study showed no statistically significant differences in soil pH, acidity, sorption properties, and granulometric composition between the different Rekulter treatments. While seemingly surprising, given the known influence of organic amendments on soil properties, this underscores the complex and multifactorial nature of soil dynamics [62,63]. Various factors, including soil type, formulation dose, and incubation time, may contribute to nuanced responses [64]. Soil behavior is complexly shaped by a variety of factors including climate, vegetation cover, and microbial activity [63]. The lack of significant differences may be due to the inherent variability within soil systems and the specific characteristics of the study. Investigation of broader environmental contexts in future studies may provide deeper insights into the effects of Rekulter on these particular soil parameters. For example, changing the study experimental design, such as opting for an incubation experiment, could potentially provide clearer results. Considering different soil types such as Luvisol or black soils instead of the typical rusty soils (Arenosols) may also be beneficial [18].

Factors such as the dose of lignite-based formulations themselves can influence soil pH, acidity, sorption properties, and granulometric composition [18]. The long duration of the multi-year field trial may have obscured any threshold effects or dose-dependent influences of amendment application on soil properties, as suggested by previous research on the effects of exogenous organic matter on soil properties [64]. In particular, studies of lignite-based amendments have shown a reduction in the bioavailability of heavy metals such as zinc, lead, and cadmium in Haplic Luvisols following amendment application [18], suggesting a potential long-term effect on soil properties.

A comprehensive understanding of the effects of organic amendments on soil properties is critical for effective soil management due to the complex interactions of various factors on soil sorption properties [19]. Recommendations for conducting incubation experiments with different soils and lignite at higher doses up to 300 t/ha are supported by the existing literature as a means to elucidate the underlying mechanisms and complexity of sorption responses. Similarly, analysis of granulometric composition highlights the intricate nature of the influence of Rekulter on soil texture. While previous studies have validated the effect of a single application of Rekulter on the physicochemical properties of rusty soils [65], the current results suggest no significant differences in granulometric composition among the variants, as indicated by the ANOVA results. This complexity underscores the need for a more thorough investigation of the interactions between Rekulter components and soil particles.

On the other hand, the study found significant improvements in OC, TN, PAHs, PCs, and fractional composition of organic matter with increasing Rekulter doses, which is consistent with previous research on the role of organic amendments in improving soil fertility [11,29–31,66,67]. Findings from the hypotheses of significant differences in OC and TN levels, PAH and PC content, and fractional composition of organic matter among different doses of Rekulter highlight dose-dependent threshold effects of Rekulter application on soil characteristics, contaminant levels, and organic matter fractions. The hypothesis of significant differences in OC and TN levels revealed a dose-dependent pattern in soil composition, indicating the importance of optimizing Rekulter application for significant improvements in soil quality. Similarly, the hypothesis of significant differences in PAH and PC content revealed a nuanced relationship between Rekulter dose and soil contamination levels, emphasizing the need for balanced application strategies. The hypothesis of significant differences in the fractional composition of organic matter provided insight into the fractional composition of organic matter, revealing dose-dependent shifts that underscore the need for precision in Rekulter application for optimal soil health [18,19].

The presence of PAHs and PCs in soil, albeit at low concentrations, raises environmental concerns due to their persistence and potential hazards [68–70]. The significant differences in contamination levels between Rekulter treatments underscore dose-dependent effects and highlight the importance of optimized application rates to mitigate environmental risks [18]. In addition, the complex interactions between PAHs and soil properties underscore potential threats to soil integrity and broader ecosystem functioning [71,72].

Optimizing Rekulter application doses based on soil characteristics and environmental considerations is critical to maximizing soil fertility while minimizing contamination risks [73]. Integrating organic amendments with mineral fertilizers can further enhance nutrient availability and improve soil structure, thereby promoting sustainable crop production [74]. In addition, implementing soil conservation practices can increase soil resilience and mitigate environmental impacts, contributing to long-term agricultural sustainability [75,76].

This study's insights into Rekulter's effects on soil organic matter composition provide a scientific basis for practical recommendations in agricultural soil management under anthropogenic pressure. By elucidating dose-dependent effects and long-term soil dynamics, this research contributes to a deeper understanding of soil responses to organic amendments. Moreover, the study resonates with broader soil science discourse, aligning with existing knowledge on soil fertility, humic substances [18], and lignite's multifunctional role in sustainable agriculture [77–80].

Although no side effects were found in the multi-year field study, the integration of the results with established scientific knowledge reinforces the potential of lignite-derived products in agricultural practice [18]. However, the study underlines the importance of cautious consideration of potential environmental risks, especially with regard to the formation of hazardous compounds such as PAHs and PCs [53,54,81–86]. Several studies have highlighted the concerns surrounding lignite's role in the generation of PAHs and PCs within agricultural contexts [53,54,81–86]. One study underscores the significance of phenolic compounds in various applications [81], while another demonstrates the effectiveness of aqueous saponin in PAH removal and biodegradation [82]. Additionally, a comprehensive review discusses remediation strategies for PAHs, emphasizing their environmental impact and ecological restoration using microorganisms [53]. Furthermore, research has explored PAH recalcitrance and the role of bacteria in biodegradation [83], as well as microbial metabolic processes for PAH breakdown in soil [84]. Another study provides insights into PAH sources, environmental impact, and remediation strategies [85]. Additionally, investigations into PAH and heavy metal detoxification in plants have been conducted [54], along with highlighting microbial degradation's potential in mitigating hazardous compound formation in soil [86].

Overall, this study provides valuable insights into the complex interactions between reclamation practices and soil parameters. Although some aspects remain inconclusive, the results underscore the tangible effects of Rekulter on various soil parameters and highlight the importance of considering dose-dependent effects in agricultural interventions. By balancing the benefits of Rekulter with careful dosage considerations, farmers can promote sustainable agriculture while minimizing environmental risks. This research not only contributes to the academic discourse, but also provides practical recommendations for soil management under anthropogenic pressures. As we continue to explore sustainable agricultural practices, understanding the nuanced effects of Rekulter on soil dynamics remains paramount for informed decision-making and environmental stewardship.

5. Conclusions

This study aimed to evaluate the impact of Rekulter, a lignite-based fertilizer, on various soil parameters, with a focus on promoting sustainable agricultural practices. Through a multi-year field trial in Klon, Poland, using various analytical techniques, the study comprehensively investigated the complex interactions between Rekulter application at varying doses and soil responses. Six research hypotheses were formulated to predict the effects of Rekulter on critical facets of soil behavior, encompassing pH, soil acidity, sorption properties, granulometric composition, soil fertility and nutrient content (OC and TN), soil contaminant (i.e., PAHs and PCs) concentrations, and fractional composition of organic matter. Analysis of Variance (ANOVA) and Tukey's HSD post hoc tests were utilized to rigorously evaluate soil characteristics, revealing significant dose-dependent effects of Rekulter on OC, TN, PAHs, PCs, and fractional organic matter composition. More specifically, ANOVA was used to assess the significance of observed differences among multiple experimental treatments, while Tukey's HSD provided detailed post hoc analysis focusing on the dose-dependent effects of different Rekulter treatments. The combined use of ANOVA and Tukey's HSD strengthened the statistical foundation of the study, allowing for a thorough examination of the complex soil responses to Rekulter application. This study demonstrates a dose-dependent response to Rekulter application across various soil parameters. Significant differences were observed in OC and TN levels among different doses, with higher doses (K4, 160 t/ha) leading to more pronounced changes compared to lower doses (K1, K2, and K3). Analysis of soil contaminants revealed significant differences in PAHs and PCs levels among treatments, with even the minimum dose showing significant deviations from untreated controls. However, further increases in Rekulter dose beyond a certain threshold did not result in significantly different contamination levels within the tested range. The study also found significant shifts in the distribution of organic matter constituents with higher Rekulter doses (K4), highlighting the importance of precision in application to optimize soil health and nutrient availability. These findings contribute valuable insights for optimizing Rekulter application in agricultural practices and underscore the need for a balanced approach to soil management and environmental stewardship. This highlights the importance of optimizing application rates to achieve effective soil management. The study adds valuable insights to the existing body of knowledge on soil dynamics under Rekulter application. These insights have practical implications for sustainable agricultural practices. By considering dose-dependent responses and long-term soil dynamics, the research facilitates informed decision-making in agricultural interventions. Ultimately, this work promotes sustainable soil management and environmental stewardship. The findings empower stakeholders to make evidence-based choices when implementing Rekulter as part of their agricultural strategies. Recommendations include tailored application rates based on soil characteristics, integration of organic amendments with mineral fertilizers, and a balanced approach to reclamation considering soil improvement and environmental concerns.

Overall, this study underscores the significance of informed decision-making in agricultural interventions, contributing valuable insights to soil management practices and environmental stewardship, while paving the way for future research in lignite-based amendments and sustainable soil management.

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Appendix A

Table A1. ANOVA pertaining to the pH value and acidity of the soil.

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	11	0.2383	0.079433	0.026725	0.99348
Residuals	56	17.83375	2.972292		

Source: own elaboration.

Table A2. ANOVA pertaining to the sorption properties of the soil.

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	3	979.4892	326.4964	2.239809	0.18414
Residuals	56	874.6183	145.7697		

Source: own elaboration.

Table A3. ANOVA pertaining to the granulometric composition of the soil.

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	3	0.030225	0.010075	0.05338	0.982709
Residuals	76	1.698675	0.188742		

Source: own elaboration.

Table A4. OC and TN (in %) in the soil, and the value of the C:N ratio.

Year	Variant/Dose	OC	$s_{\overline{OC}}$	TN	$s_{\overline{TN}}$	C:N
1st	K1	0.76	0.0212	0.06	0.0042	13
1st	K2	1.08	0.0170	0.08	0.0057	14
1st	K3	1.45	0.0255	0.09	0.0042	16
1st	K4	2.21	0.0354	0.11	0.0071	20
2nd	K1	0.77	0.0183	0.05	0.0042	15
2nd	K2	1.05	0.0156	0.07	0.0057	15
2nd	K3	1.44	0.0226	0.07	0.0042	21
2nd	K4	2.17	0.0311	0.10	0.0071	22

Table A4. *Cont.*

Year	Variant/Dose	OC	$s_{\overline{OC}}$	TN	$s_{\overline{TN}}$	C:N
3rd	K1	0.79	0.0198	0.05	0.0042	16
3rd	K2	1.00	0.0141	0.07	0.0057	14
3rd	K3	1.35	0.0240	0.09	0.0042	15
3rd	K4	2.13	0.0339	0.11	0.0071	19
4th	K1	0.84	0.0226	0.05	0.0042	17
4th	K2	1.16	0.0198	0.07	0.0057	17
4th	K3	1.57	0.0283	0.08	0.0042	20
4th	K4	2.26	0.0397	0.10	0.0071	23
5th	K1	0.87	0.0240	0.05	0.0042	17
5th	K2	1.15	0.0226	0.07	0.0057	16
5th	K3	1.50	0.0268	0.08	0.0042	19
5th	K4	2.27	0.0367	0.09	0.0071	25
22nd	K1	0.76	0.0212	0.07	0.0042	11
22nd	K2	1.08	0.0170	0.08	0.0057	14
22nd	K3	1.41	0.0240	0.08	0.0042	18
22nd	K4	2.17	0.0354	0.09	0.0071	24

Source: own elaboration; Note: $s_{\overline{OC}}$, $s_{\overline{TN}}$ denote the standard errors associated with the OC and TN parameters, respectively.

Table A5. ANOVA pertaining to the levels of organic carbon (OC) and total nitrogen (TN).

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	3	98.87743	32.95914	10.27104	0.000012
Residuals	66	211.79	3.208939		

Source: own elaboration.

Table A6. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the levels of organic carbon (OC) and total nitrogen (TN).

Pairs	diff	lwr	upr	*p* adj
K2-K1	0.157778	−1.41605	1.731608	0.993479
K3-K1	1.338333	−0.2355	2.912163	0.122857
K4-K1	2.927222	1.353392	4.501052	0.000039
K3-K2	1.180556	−0.39327	2.754385	0.207066
K4-K2	2.769444	1.195615	4.343274	0.000099
K4-K3	1.588889	0.015059	3.162719	0.046993

Source: own elaboration.

Table A7. ANOVA pertaining to the contents of PAHs and PCs in the soil.

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	3	36876.83	12292.28	5.562676	0.009057
Residuals	114	33146.67	2209.778		

Source: own elaboration.

Table A8. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the contents of PAHs and PCs in soil.

Pairs	diff	lwr	upr	*p* adj.
K2-K1	−76.1667	−154.389	2.055538	0.048602
K3-K1	−103	−181.222	−24.7778	0.008517
K4-K1	−83.8333	−162.056	−5.61113	0.033777
K3-K2	−26.8333	−105.056	51.38887	0.757946
K4-K2	−7.66667	−85.8889	70.55554	0.991804
K4-K3	19.16667	−59.0555	97.38887	0.893066

Source: own elaboration.

Table A9. ANOVA pertaining to the fractional composition of organic matter (in g/kg of soil).

	Df	Sum Sq	Mean Sq	F Value	Pr (>F)
Variant	3	106.9017	35.63391	8.97283	0.000214
Residuals	209	119.1394	3.971312		

Source: own elaboration.

Table A10. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the fractional composition of organic matter (in g/kg of soil).

Variant	diff	lwr	upr	*p* adj
K2-K1	0.542727	−1.76781	2.853261	0.918627
K3-K1	2.035455	−0.27508	4.345988	0.099711
K4-K1	4.020909	1.710375	6.331443	0.000277
K3-K2	1.492727	−0.81781	3.803261	0.313505
K4-K2	3.478182	1.167648	5.788716	0.001598
K4-K3	1.985455	−0.32508	4.295988	0.112241

Source: own elaboration.

Table A11. ANOVA pertaining to the fractional composition of organic matter (in % OC).

	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
Variant	3	316.1008	105.3669	3.876915	0.019951
Residuals	209	733.8067	27.17803		

Source: own elaboration.

Table A12. Results from the Tukey's Honestly Significant Difference (HSD) test pertaining to the fractional composition of organic matter (in % OC).

Variant	diff	lwr	upr	*p* adj.
K2-K1	−6.69	−13.0701	−0.30987	0.037241
K3-K1	−2.36	−8.74013	4.02013	0.743727
K4-K1	−6.4	−12.7801	−0.01987	0.049077
K3-K2	4.33	−2.05013	10.71013	0.269815
K4-K2	0.29	−6.09013	6.67013	0.999294
K4-K3	−4.04	−10.4201	2.34013	0.327021

Source: own elaboration.

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