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Impact of sewage sludge addition on Dexter soil quality index

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Abstract: Assessing soil quality is essential for sustainable land use and agricultural productivity, particularly in the case of degraded, sandy, or low-organic-matter soils that suffer from poor water retention and reduced biological activity. One promising tool in this context is the Dexter soil quality index (*S*-index), which focuses on the relationship between volumetric water content and soil structure stability. Unlike general soil quality indices (*SQI*) that often integrate chemical or biological indicators, the *S* index offers a more physically grounded and quantifiable parameter for evaluating soil physical quality and water availability. It is particularly valuable for monitoring changes following organic amendments such as sewage sludge. The aim of this study was to evaluate the influence of sewage sludge application on the Dexter *S*-index, as an indicator of improved soil usability in terms of volumetric water content and retention capacity. The research was based on controlled pot experiments involving three mineral soil types: sandy-loam clay, loose sand, and clayey silt. Each soil type was amended with sewage sludge at rates equivalent to 50, 100, and 200 $Mg\cdot ha^{-1}$. The results showed a clear increase in the *S*-index with increasing sludge doses across all soil types. The greatest relative improvements were observed in light-textured soils (0.042), where the original *S* values were lowest (0.018). This confirms the positive effect of sewage sludge on enhancing soil structure and water availability, particularly in sandy soils with inherently low retention capacity.

Keywords: fertilisation, sewage sludge, soil quality, soil health, water characteristics of soil

INTRODUCTION

The use of sewage sludge for soil fertilisation remains popular because it provides an opportunity to recycle valuable components such as phosphorus, nitrogen, organic matter, and other plant nutrients. Yields from crops appropriately fertilised with sewage sludge are generally higher than from soil enriched with conventional fertilisers. However, some authors have observed a decrease in yields and poorer plant growth after the application of large doses of sewage sludge for fertilisation (Stańczyk-Mazanek, 2012). Studies have confirmed that the application of sewage sludge enriches the physicochemical properties of the soil, including increased infiltration rate, aggregate stability, and water-holding capacity, alongside a rise in organic matter content (Obbard, 2001; Fytili and Zabaniotou, 2008). Sewage sludges usually enhance the water and physical properties of soils, although this largely depends on the specific characteristics of the soils to which they are applied. Kusza (2006) applying sewage sludge for the reclamation of soils in open-cast limestone mining areas, found that there was no significant change in physical parameters, such as volumetric soil dry density (*VSDD*) and capillary water-holding capacity (*CWH*). The volumetric soil density increased by only about 8% in the plots with sewage sludge. Neverthless, the use of sewage sludge significantly enriched the restored soil with organic matter. Essentially bare soil achieved typical organic matter content (2.17%) and even higher levels (3.53%) than in cultivated soils. Applying sewage sludge to soil leads to significant changes in microbiological activity, which are useful for assessing soil fertility. This includes changes in the abundance of microbial groups responsible for nitrification, ammonification, mineralisation, and humification, as well as their enzymatic activity, production of specific metabolites, and CO_2 emission. In soil science literature, numerous morphological features and biological, physical, chemical, physicochemical properties associated with the conditions leading in the soil and its functional roles are considered as indicators of soil health, conditions and quality (Sharma *et al.*, 2023; Celis *et al.*, 2024). Depending on the type of land use – whether it's agricultural, meadow, or forested – specific indicators play a greater or lesser role (Reynolds *et al.*, 2008; Schoenholtz, Miegroet van and Burger, 2000; Brożek, 2007).

The water content level prevailing in soils significantly influence their thermal properties and determine the effects of mechanical interactions on soils during agricultural practices. Understanding the water and air properties is essential for interpreting and predicting the course of all physical, chemical, and biological processes occurring in soils (Dexter, 1997; Walczak *et al.*, 2002). Criteria for appraising the physical quality of soil have also been suggested using synthetic indicators derived through mathematical methods. One such indicator is the *S*-index developed by Dexter. Based on extensive research (Dexter, 2004a; Dexter, 2004b; Dexter, 2009) suggested adopting the soil physical quality index (S-index) as a general method for determining the physical properties across all soil types. According to the author, this index, characterised as the tangent of the slope at the inflection point of the soil water retention curve, this index reflects key aspects of soil structure. The curve illustrating water retention is based on plotting the natural log of soil water potential against its gravimetric moisture content ($kg \cdot kg^{-1}$). At the inflection point of the water retention curve lies the transition between structural porosity, formed by fissures, biological channels, and inter-aggregate voids affected by land management, and matrix porosity, located within aggregates and between grains, determined by particle size distribution. The author proposed the (Tab. 1) soil quality levels defined according to the calculated parameters of the *S*-index values (Dexter, Czyż and Gațe, 2007b). The *S* value of 0.035, considered the transition point between good and poor quality, was established according to the maximum density values of various soil types. Fitting the model of water retention curve to the van Genuchten equation (Genuchten van, 1980) is intended to provide a standardised and impartial technique used to detect the inflection point and carry out calculations of the soil physical quality index (*S*-index).

Authors (Dexter, Czyż, 2007; Dexter, Czyż and Gațe, 2007a; Dexter, Czyż and Gațe 2007b) propose calling the use of the *S*-index for research purposes of the "*S* theory". According to the author, directly from the *S*-index value, other physical properties of soils can be assessed, such as crusting, ease of cultivation, saturated hydraulic conductivity, unsaturated hydraulic conductivity and soil compactness. The author states that the *S*-index can be a valuable tool for assessing degradation or adjustment in the physical properties of soil quality and can also serve in evaluating the physical quality of global soil resources. Simultaneously, he acknowledges that *S*-index belongs to the group scale of the numerical methods for assessing the physical quality of soil and does not cover all possible cases, such as waterlogged soils unsuitable for cultivation for a significant part of the year, and certain types of sands (Dexter, 2004a; Kutílek, 2004).

According to Choundhury and Mandal (2021), the *S*-index provides a straightforward range that maintains equivalent physical significance without regard to the soil type. Thus, it facilitates the comparative analysis of soil physical quality (*SPQ*) in relation to soil depth variations, diverse soil categories, and differing spatial scales. Degradation of soil structure leads to modifications in the soil water retention curve (*SWRC*), which in turn affects the *S*-index and how soil physical quality (*SPQ*) is evaluated. Naderi-Boldaji and Keller (2016) proposed the physical soil parameter *S* (*S*-index or *S*-value) used to evaluate physical properties of the soil. As referenced to them, soil compaction (e.g., induced by agricultural activities) adversely impacts the soil's physical quality. It was previously demonstrated that *S* declines as soil bulk density increases.

The experiment identifies a correlation between the *S* parameter and soil compactness, which can be described through a unified function. This becomes especially significant across different soil textures when compactness is expressed as the degree of compactness (*DC*), defined by the ratio of bulk density to a reference density. Laboratory findings regarding *S* from existing literature corroborate these conclusions. The expected value of *S* (0.035), previously proposed as the threshold between high-quality and low-quality soil physical conditions, fits closely with the *DC* level (87%) recognised in research as essential for plant growth. Experiments conducted by Naderi-Boldaji *et al.* (2016) indicates that $1 \cdot S^{-1}$ provides an effective assessment of soil compaction and validates the use of *S* as a meaningful indicator of physical soil properties.

The factors affecting soil water retention were analysed with respect to both hydraulic and thermodynamic equilibrium conditions (Dexter, Czyż and Richard, 2012). The Groenevelt and Grant water retention equation is considered to characterise soil water behaviour near thermodynamic equilibrium. Previous studies have demonstrated the occurrence of non-equilibrium displacement under certain experimental conditions. In pressure cell systems, for instance, the forced movement of water by compressed air can lead to incomplete drainage of soil pores. As a result, a portion of soil moisture remains that does not conform to thermodynamic equilibrium. This remaining water, however, is considered to be in hydraulic equilibrium.

As the system nears hydraulic balance, the rate of water drainage decreases significantly before ceasing altogether. In soils with bimodal pore distributions, empirical models are employed to characterise water retention where residual moisture persists. It was found by Darcian convective flow that this residual water persists following the discharge of water from interconnected textural pores capable of drainage. The point where Darcian flow stopped is identified as the hydraulic cut-off. Once hydraulic continuity is interrupted, residual water remains and migrates predominantly through vapour diffusion, moving much slower than liquid-phase drainage. The suction in its pore spaces tends to be far below the pressure imposed by the pressure cell apparatus. A series of models were applied to forecast residual water content and tension in 14 soil samples from Poland and France. The outcomes provide valuable implications for both laboratory retention analysis and practical field hydration assessment (Choundhury and Mandal, 2021). In challenging soil conditions, desiccation leads to increased hardness and compaction, making agricultural operations impractical without rewetting.

The objective of study conducted by the authors was to quantitatively assess soil hardening behaviour across nine soils representing a broad spectrum of textures, ranging from sandy clay to silty clay. The preparation of packed soil cores was carried out with minimal interference to the structure of soil aggregates (0.5–4.0 mm). Water retention characteristics of soils were assessed throughout a defined spectrum of matric suction values from 10 to 15,000 hPa at various degrees of soil density (from 1.20 to 1.70 $Mg \cdot m^{-3}$). The van Genuchten–Mualem (VG-M) model for single porosity and Dexter's dual porosity approach were fitted to the observed soil water retention data. Indicators of hardening (*H*Dexter) and soil physical quality (*S*) were derived from the VG-M parameters. The physical quality of the soil was further characterised using two indices, S_1 and S_2, which represent the slopes of the water retention curve at its first and second inflection points, corresponding respectively to matrix and structural pore spaces. Additionally, new hardness metrics (H_1 and H_2) linked to matrix and structural porosity were computed using criteria from the dual porosity framework.

To evaluate mechanical strength under varying compaction levels, soil samples with different bulk densities were prepared and their tensile strength (*Y*) was measured during a drying process ranging from near saturation to oven-dry conditions. The slope of the water content–tensile strength (*Y*) relationship served as an indicator of soil hardness, with steeper inclinations suggesting a stronger tendency for hardening. As bulk density increased, the values of soil physical quality parameters (*S*, S_1, and S_2) – declined, while hardening indicators such as *H*Dexter, H_1, and H_2 increased correspondingly. Notable positive correlations were found between calcium carbonate content and the hardness indices *H*Dexter and H_1. Linear analyses revealed negative trends between bulk density and the soil quality indicators (*S*, S_1, S_2), while direct positive relationships were established between bulk density and hardness metrics (*H*Dexter, H_1, H_2). Bulk density showed a strong overall association with both soil hardness and physical quality indicators. Specifically, hardness indicators based on tensile strength exhibited positive correlations with bulk density, whereas H_2 demonstrated a significant positive relationship and S_1 a significant negative one.

These results validate the applicability of the newly developed indicators for predicting soil hardening behaviour exclusively from water retention data. This approach eliminates the need for direct mechanical strength measurements (Farahania *et al.*, 2019). Soil moisture content or its corresponding potential can be regulated under laboratory conditions by equilibrating samples at specific relative humidity levels. These humidity levels are achieved either through saturated salt solutions or by subjecting the soil to varying temperatures in a convection oven. Typically, the equilibrium is expressed as relative humidity when salt-based methods are used, or as drying temperature when oven-drying is applied. This creates a methodological discrepancy that prevents straightforward comparison or representation on a unified graph. To address this, the Kelvin equation, in conjunction with the Magnus–Tetens and Arden Buck formulations, is employed to convert both types of measurements into a common scale, such as water potential or p*F*. These equations enable estimation (Zeitoun *et al.*, 2021) of the water potential resulting from oven-drying, accounting for diverse ambient and oven conditions. The accuracy of these predictions is evaluated by comparing water retention data obtained via oven-drying with those from saturated salt equilibration. Results show that the absolute error in gravimetric water content is approximately 2.3 $g \cdot kg^{-1}$. Additionally, the amount of adsorbed water is projected to reach zero at p*F* 6.6 (Li *et al.*, 2018; Choundhury and Mandal, 2021). A study was carried out on subsoil seeding (OSSS), a reclamation technique involving the application of a synthetic soil mixture to rehabilitate cut slopes.

Vegetative cover plays a crucial role in mitigating soil erosion, improving soil quality, and fostering ecological recovery. However, there is ongoing debate among researchers regarding which vegetation types are most effective in enhancing the properties of artificial soils and stabilising slope structures. To assess the impact of different vegetation restoration approaches on artificial soils treated with OSSS, soil samples were collected from four slope treatments:

– HS – slopes restored exclusively with forbs,
– MSI – slopes with a mix of forbs and shrubs (type I),
– MSII – slopes featuring trees, herbs, and shrubs (type II),
– NS – naturally restored slopes without artificial intervention.

Three slope sites were selected for each treatment. Soil properties were evaluated across physical, chemical, biological, and structural dimensions, including metrics such as fractal dimension, deviation coefficient, structural damage index, convexity peak coefficient, and erosion rates. To calculate the soil quality index (*SQI*), both monotonic functions and principal component analysis (PCA) were employed. The results revealed marked differences in basic soil traits, structural attributes, and *SQI* between HS and the other treatments. However, except for *SQI*, MSI and MSII showed no significant differences. These findings suggest that HS is less suitable for long-term restoration, while MSII represents a more effective vegetative strategy for ecological recovery. Despite restoration efforts, artificial slope soils still differ notably from NS soils, largely due to the latter's natural optimisation over time without human interference. This highlights the need for more effective management practices to support sustainable restoration of cut slopes (Pereira Valani, Machado Vezzani and Cavalieri-Polizeli, 2020). A study was undertaken across two farms to evaluate soil quality using the rapid soil structure diagnosis method (DRES). Researchers applied three assessment tools DRES, practical guide for participatory assessment of soil quality (PGPE) and the soil management assessment framework (SMAF) to soils managed under various practices. Then they analysed the relationships between the outcomes of DRES and PGPE with SMAF-based evaluations. Soil samples were collected from Cambisols, spanning systems such as conventional farming, no-till, organic agriculture, agroforestry, and native vegetation. Samples were taken from a depth of 0–25 cm in two subtropical municipalities in southern Brazil.

The SMAF integrated six key indicators (macroaggregate stability, pH, bulk density, total organic carbon, microbial biomass carbon, and available phosphorus) into a unified soil quality index. The DRES approach assessed structural and biological conditions directly on-farm, considering attributes such as aggregation, compaction, cracking resistance, root development, and microbial activity. The PGPE similarly compiled field-based observations, including organic matter content, rooting systems, soil structure, compaction, infiltration, erosion, water retention, macrofauna presence, and ground cover, to generate its own index of soil quality.

Both DRES and PGPE effectively distinguished differences among management systems, with SMAF serving as an analytical benchmark. Notably, PGPE provided greater spatial differentiation than DRES, regardless of municipality or soil texture, and showed stronger alignment with SMAF results, especially in clay-rich soils. These findings underscore the value of practical, on-farm soil evaluation tools, which deliver timely and interpretable insights for guiding land management decisions.

According to Al-Kayssi (2021), gypsum-binding soils harden and become compact when they dry, independent of any compaction resulting from farming practices. As a result, these soils can be challenging or even impossible to farm unless they are rehydrated. Earlier research has shown that compaction adversely impacts *S*-index. The study aimed to quantitatively evaluate soil hardness and compaction, using the degree of compactness (*DC*) – a metric derived from the ratio of bulk density to a reference density. The assessment was based on water retention data and a physical soil quality index across fifteen soils with varying levels of gypsum content (ranging from 30 to 301 $g \cdot kg^{-1}$). Disturbed soil cores were collected with minimal disturbance to the soil aggregates (≤4 mm). Soil water retention curves were assessed within a matrix suction range of 10 to 15,000 hPa. A version of the van Genuchten–Mualem model configured to describe single-porosity behaviour in soils was applied to the water retention data. Computations were performed for the *S* index and Dexter hardsetting (*H*Dexter) utilising the parameters from the van Genuchten–Mualem model. The research investigated how the *S* index correlates with the desorption curve (*DCu*) and *H*Dexter across 15 gypsum-rich soils. Strong polynomial and power associations were detected between *DC* and *H*Dexter, along with the *S*-index (i.e., 1/*S*), which were significant across different gypsum concentrations within the soils. Additionally, notable negative correlations between *H*Dexter and the gypsum content of the soil were found. The analysis revealed upward polynomial trends linking the *S*-index with bulk density, while *H*Dexter also demonstrated a polynomial association with bulk density. Additionally, positive correlations were identified between *H*Dexter, *DCu*, and relative bulk density. There were also positive associations recognised between *H*Dexter, *DCu*, and relative bulk density. These results confirmed that the newly introduced *H*Dexter index effectively predicts soil hardening behaviour and quantitatively assesses the physical quality of gypsum-containing soils based solely on water retention data, negating the need for mechanical strength measurements.

Monteiro Cavalcante *et al.* (2021) indicate that soil physical quality (*SPQ*) functions as a core determinant in crop development. While it is well acknowledged that crop management significantly impacts *SPQ*, this relationship is complex in Vertisols due to their shrink-swell behaviour. This analysis aimed to (i) evaluate how various cultivation methods influence *SPQ*, as indicated by the *S*-index, least limiting water range (*LLWR*), and percentage of water stress (*PW*) and (ii) investigate the relationships between these *SPQ* indicators and crop yields. A four-year field study was conducted on Vertisol soils in the North China Plain (Wang *et al*., 2021) under a wheat–maize crop rotation system, applying four distinct tillage practices: rotational tillage (RT), no-tillage (NT), subsoiling (SS), and deep ploughing (DP). Throughout the growth periods of wheat and maize, soil measurements were taken from the top two layers (0–10 cm and 10–20 cm), capturing data on the soil water retention curve (*SWRC*), soil shrinkage curve (*SSC*), penetration resistance (*PR*), and bulk density (*BD*), alongside continuous *in situ* monitoring of soil moisture. Based on these measurements, values for the *S*-index, *LLWR*, and *PW* were derived.

The results indicated that *SSC* remained consistent across all four tillage treatments, implying that cultivation method had no statistically significant effect on shrinkage behaviour ($p > 0.05$). Compared to no-tillage (NT) and rotational tillage (RT), subsoiling (SS) and deep ploughing (DP) contributed to improved soil physical quality, evident through elevated *S* index values and expanded *LLWR*, particularly within the 10–20 cm soil depth. While the *S*-index exhibited weak correlations with wheat and maize yields ($p > 0.05$ for both), *LLWR* showed a significant association with wheat yield ($p < 0.05$), but not with maize ($p > 0.05$). A novel indicator, the *SPQI*, was proposed to quantify the proportion of the growing season during which soil moisture levels exceed field capacity (water logging potential – *WLP*, representing irrigation-related stress) or fall below the wilting point (reflecting drought-related stress potential – *DSP*). Notably, *WLP* demonstrated a strong negative correlation with maize yield ($p < 0.01$), whereas no significant link was observed with wheat yield ($p > 0.05$), while *DSP* did not show any correlation with yields for either crop ($p > 0.05$). Additionally, it was noted that WSP is unaffected by volume fluctuations in Vertisol. These findings suggest that both *LLWR* and WLP could serve as effective indicators for evaluating soil physical quality in wheat and maize during their growing seasons, with WLP being particularly suited for application in Vertisol. Calero *et al.* (2018) highlight that despite the significance of quality in agronomic and soil research, implementing this concept remains complex due to the interplay of theory and empirical techniques in under-researched areas where procedural methods are not yet well defined.

In their article, the authors introduce a novel technique that infrequently utilises qualitative morpho-pedological data, organised within a single field soil quality index (*FSQI*). The study leverages nonlinear PCA for dimensionality reduction and data structure analysis, which is suited for processing categorical data, to manage morpho-pedo indicators. By converting categorical values, the data can be effectively examinated and interpreted. This approach requires less specialised knowledge, making it beneficial for non-experts evaluating soil quality. The *FSQI* methodology was employed to examine soil cultivation practices on a global scale, with specific attention given to Jaén Province in southern Spain – a region currently facing significant challenges related to soil degradation and erosion. To support the analysis, researchers compiled a comprehensive soil database encompassing 18 morphological parameters across 131 surface strata, representing a diverse range of land use types. Nonlinear principal component analysis (NLPCA) was further employed to systematically scale and assign weights to the selected attributes, facilitating the integration of morphological indicators into a simplified weighted additive index – *FSQI*. The derived scaling functions and weighting coefficients were then used to assess the attributes, considering two distinct soil management strategies: conventional and organic systems in olive groves. The mean *FSQI* value was notably lower in conventionally managed olive groves than in those under organic cultivation (0.278 compared to 0.463, $p < 0.05$), supporting the index's validity. A dedicated *FSQI* web service was developed to aid decision-making in the investigated region, and the methodology demonstrates applicability across diverse regions and agricultural crops.

Nascimento *et al.* (2021) highlight the importance of researching land degradation for environmental conservation. With approximately 30% of the world's soils affected by degradation, it is essential to investigate and map these areas to improve their management and use. The objective of their study was to create a soil degradation index (*SDI*) utilising temporally distributed satellite datasets imagery in conjunction with climatic data, terrain features, land use, and soil characteristics. The study covered a 2.598 km^2 area in São Paulo, Brazil, where a total of 1,562 soil samples – taken from depths of 0 to 20 cm – were collected and examined through conventional analytical techniques. Machine learning techniques were utilised to produce spatial estimations of key soil characteristics, such as clay percentage, cation exchange capacity (*CEC*), and organic matter (OM) levels. A 35-year Landsat image archive was utilised to construct a multi-temporal soil imagery dataset, leveraging its spectral bands as predictive variables for soil properties. Spatial layers representing clay concentration, cation exchange capacity (*CEC*), climatic conditions, topography, and land use were integrated. Soil degradation was classified into five distinct levels – ranging from very low (class 1) to very high (class 5) – using the *K*-means clustering algorithm. Validation of the soil degradation index (*SDI*) was performed using predicted OM distribution, confirming that class 5, the most degraded category, covered 15% of the study area and corresponded to the lowest OM levels. Classes 1 and 4 emerged as the most dominant, representing 24% and 23% of the region. Thus, the integration of satellite imagery with environmental data played a significant role in developing the *SDI*, aiding in informed decision-making for spatial planning and management.

The research conducted by Panagos *et al.* (2015) highlights water erosion as a significant risk to soils within the European Union, adversely affecting ecosystem services, drinking water quality, agricultural output, and carbon stocks. The European Commission's Soil Thematic Strategy recognises soil erosion as a vital concern and suggests a framework for monitoring it. This study highlights the application of RUSLE2015, an enhanced version of the revised universal soil loss equation, to quantify soil erosion across Europe using data from the reference year 2010. In this analysis, various factors influencing erosion – including rainfall erosion, soil susceptibility, land cover management, topography, and conservation practices – were modelled using the most recent pan-European datasets, which were updated in 2010 and feature a high resolution of 100 m. The estimated average soil loss rate (erosion intensity) in vulnerable areas of the EU area (including agricultural, forest, and semi-natural regions) stands at 2.46 Mg·ha^{-1}·y^{-1}, culminating an estimated yearly soil erosion of 970 Tg. A notable added value of RUSLE2015 is its capacity to assess the impacts of policy scenarios related to land use transormation and conservation strategies.

The adoption of sustainable agricultural practices in accordance with the good agricultural and environmental conditions (GAEC) under the common agricultural policy (CAP), along with EU soil protection directives, has been categorised into two main approaches: land management strategies – including reduced or no-tillage systems, incorporation of crop residues, and the use of cover crops – and supportive conservation measures, such as contour cultivation and the maintenance of stone walls and vegetative buffer zones. Over the past ten years, these policy-driven interventions—particularly those stemming from GAEC standards and the Soil Thematic Strategy – have contributed to a 9.5% average reduction in soil erosion across Europe, with arable land experiencing a more pronounced decline of 20% in soil loss. Particular focus is being placed on 4 mln ha of farmland that currently experience unviable soil loss rates exceeding 5 Mg·ha^{-1}·y^{-1}, which should be the target for these policy measures. Among various soil indicators used to assess physical properties, the *S*-index, a widely cited indicator derived from the slope of the soil water retention curve at its inflection point, was critically examined by Santos *et al.* (2011). Their study underscores the influence of the chosen independent variable – specifically suction – on the resulting *S*-index values. They demonstrated that employing an arithmetic scale for suction, rather than a logarithmic transformation, yields different outcomes for the same soil. More broadly, their findings advocate for the use of water retention curves plotted with arithmetic suction expressions, suggesting this approach offers enhanced analytical potential over conventional methods that rely on natural or decimal logarithmic scales. The results reveal that selecting $\ln(h)$ or $\log(h)$ instead of h as the independent variable can significantly alter the calculated *S*-index. Using suction (h) as the independent variable in *S*-index data processing has been demonstrated to be both mathematically sound and physically meaningful. The authors further illustrate that the selection of the independent variable can constrain the physical interpretation of soil properties. In the case of the soil analysed, their findings confirm that computing the *S*-index using suction (h) as the independent variable notably enhances analytical precision when compared to the range of *S*-values obtained through Dexter's original formulation (Dexter and Czyż, 2007; Dexter, Czyż and Gaţe, 2007a; Dexter, Czyż and Gaţe, 2007b).

Further inquiry will be directed toward understanding the implications of this variable on the *S*-index across diverse soil types and determining if using h enhances the sensitivity of the analysis. Adhering to the appropriate range of organic carbon percentage (*OC%*), bulk density (*BD*), and *S*-index shows a strong correlation with other soil characteristics, regardless of soil texture.. The findings indicate that soil density must exceed 1.8 g·cm^{-3} to face physical degradation, which adversely impacts the soil's functional capabilities. Dexter (2004a) proposes an estimated *S*-end degradation of 0.035 (or lower). This analysis could be expanded with a larger dataset, organised by regression according to specific textural classes. Moreover, this has practical significance, as *BD* measurable in the field with known volume ring samples can serve as a proxy for *SPQ* (Fenton *et al.*, 2017).

The technique for assessing the amount of dispersed clay in soil relative to water was outlined (Czyż and Dexter, 2015). This approach was validated through soil sampling conducted at 18 distinct agricultural locations throughout Poland. A suite of soil parameters – including particle size distribution, organic matter content, and concentrations of exchangeable cations – was evaluated using standardised analytical methods. Soil subsamples were immersed in distilled water and subjected to four distinct mechanical energy levels, modulated by varying the number of end-over-end inversions. The resulting concentration of dispersed clay particles in suspension was quantified via turbidimetric light scattering analysis. An observational model equation was formulated, which closely matched the experimental data, relating turbidity to the number of inversions. This allows for the prediction of spontaneously dispersed clay quantity by extrapolating the equation to zero inversions. The method offers a shift from the previous subjective and qualitative approach to a more quantitative and objective assessment of spontaneously dispersed clay. Despite saturation during measurement, the soil exhibits a persistent memory of its prior water content. Research has highlighted the significance of factors such as bulk density, the amount of easily dispersible clay, organic matter content, and fluorescein diacetate hydrolysis in sustaining soil functionality (Gajda, Czyż and Dexter, 2016). The aim of this article is to assess the usefulness of the *S*-index as a universal tool for assessing soil physical quality in various soil types, with particular emphasis on the relationship between the *S*-index and the p*F* curve for the various soil types analysed. The aim of this study is also to determine whether the $1 \cdot S^{-1}$ parameter can serve as an effective measure of soil quality after sewage sludge application and whether this improves soil water retention, which is considered critical for plant growth.

The novelty of this study lies in linking the *S*-index with p*F* curve values after application of sewage sludge with high organic matter content across a wide range of soil textures and demonstrating a strong correlation between *S* and p*F*, enabling universal application of this index in agricultural and environmental practices. Additionally, a detailed quantitative assessment of the effect of sewage sludge addition on changes in the retention properties of mineral soils and an analysis of the sensitivity of the Dexter model to sewage sludge.

MATERIALS AND METHODS

SAMPLING AND PREPARATION OF SAMPLES

The soil material used for pot experiments (loose sand, sandy-loam clay, clayey silt) was sourced from the Płoki village in the Trzebinia municipality (Poland). The pot tests were the repeated under similar temperature and humidity conditions to ensure consistence of samples. To conduct the study, three identical samples for all soil types were collected from each analysed point, weighing approximately 5 kg, from a depth of 20–40 cm below the ground surface. The scope covers the so-called arable-root layer, the zone where most active crop roots are located and where key biological and chemical processes occur. Analysis of this layer provides representative information on soil nutrient content, structure, organic matter content, and compaction, all of which are crucial for plant growth and yield. Additionally, sampling from this depth allows for the assessment of the impact of agricultural practices (e.g., ploughing, fertilisation, compaction) on soil physical and chemical properties and allows for monitoring changes in the soil as a result of long-term use. These samples were then sieved and homogenised. To ensure repeatability, sampling was limited to an area of 25 × 25 m for each soil type. A control (blank sample) was also used, not subjected to mixing with sewage sludge. Sewage sludge used in the experiments originated from the sewage treatment plant in Trepcza near Sanok (Poland). The treatment plant employs a two-stage purification process: the first stage involves mechanical methods using screens, sand tanks, and settlers, while the second stage is biological, incorporating aeration and fermentation chambers. In the pot experiment, three fertilisation doses of sewage sludge were applied, twice for each soil type, at doses similar to 50, 100, and 200 $Mg \cdot ha^{-1}$. Two pots were allocated for each soil type without the addition of sewage sludge.

LABORATORY TESTS

The water characteristic curve was determined using the centrifuge method (Vero *et al.*, 2013). A centrifuge MPW-352R (MPW Med. Instruments, Poland) (4 rpm) was used for this purpose: 500 (corresponding to p*F* = 1.33; 22 kPa), 1,000 (p*F* = 1.94; 87 kPa), 3000 (p*F* = 2.89; 775 kPa), 5000 (p*F* = 3.33; 2,159 kPa). The humidity corresponding to the point of maximum hygroscopicity (p*F* = 4.7) was determined in a vacuum chamber saturated with potassium sulphate at a negative pressure of 400 bar moisture content at the permanent wilting point (p*F* = 4.2) was determined based on the moisture content at the point of maximum hygroscopicity (Mocek, 2015). The water characteristic curves were parameterised to the van Genuchten equation. The soil quality index, determined by Dexter's method (*S*), was calculated based on:

$$S = \frac{\rho_w}{\rho_o} \cdot (\theta_s - \theta_r) \cdot n \cdot \left(\frac{2 \cdot n - 1}{n - 1} \right)^{\frac{1}{n} - 2} \tag{1}$$

STATISTICAL EVALUATION OF DATA

Statistical analysis was conducted using the Statistica 13 software package (StatSoft Inc.), which enabled the implementation of advanced computational procedures, including analysis of variance (ANOVA), significance testing between groups, correlation analysis, and linear regression. The significance level was set at $p < 0.05$. The use of this tool allowed for precise evaluation of relationships between the studied variables and facilitated the visualisation of results in the form of graphs and tables, thereby enhancing the interpretation of empirical data and statistical inference. The obtained values were compared with those proposed by Dexter, Czyż and Gațe (2007b) – Table 1.

Table 1. Dexter's proposals for the following soil physical quality categories based on the calculated soil physical quality index (*S*-index)

Soil quality	Value of *S*-index (–)
Very poor	<0.020
Poor	0.020–0.035
Good	>0.035–0.050
Very good	>0.050

Source: own elaboration based on: Dexter (2004a), Dexter (2004b), and Dexter (2004c).

RESULTS AND DISCUSSION

Data from the conducted research were collected and summarised in Table 2 and subsequently subjected to statistical analysis. Descriptive statistics, including means and standard deviations, were first calculated to provide an overview of the data distribution. Next, a one-way analysis of variance (ANOVA) was performed to examine potential differences between the studied groups.

For p*F* values, the *SD* is relatively low, indicating high repeatability of the measurements. The difference was not significant compared to the control sample. The results of the statistical analysis of the data collected during the study are summarised in Table 3. Statistical analysis was performed using

Table 2. Results of volumetric water content determinations at points corresponding to soil water potential p*F*: 1.33, 1.94, 2.89, and 3.33 in the centrifuge method and points 4.2 and 4.7 in the vacuum chamber saturation method

Soil	Sludge portion ($Mg \cdot ha^{-1}$)	Repetitions	Volumetric water content ($cm^3 \cdot cm^{-3}$) at p*F*						
			0	1.33	1.94	2.89	3.33	4.20	4.70
Loose sand	0	1	0.319	0.291	0.211	0.090	0.068	0.044	0.040
		2	0.323	0.297	0.195	0.092	0.060	0.038	0.035
		3	0.340	0.312	0.189	0.103	0.080	0.029	0.049
		average	0.327	0.300	0.198	0.095	0.070	0.037	0.041
		SD	0.011	0.011	0.011	0.007	0.011	0.008	0.007
	50	1	0.408	0.364	0.272	0.149	0.110	0.059	0.054
		2	0.416	0.358	0.276	0.147	0.104	0.053	0.048
		3	0.384	0.385	0.245	0.168	0.135	0.046	0.068
		average	0.403	0.369	0.264	0.155	0.116	0.053	0.057
		SD	0.017	0.014	0.017	0.012	0.016	0.007	0.010
	100	1	0.439	0.386	0.316	0.195	0.150	0.082	0.075
		2	0.435	0.384	0.310	0.193	0.158	0.076	0.069
		3	0.425	0.395	0.300	0.185	0.146	0.101	0.062
		average	0.433	0.388	0.309	0.191	0.151	0.086	0.069
		SD	0.007	0.006	0.008	0.005	0.006	0.013	0.007
	200	1	0.468	0.452	0.437	0.145	0.131	0.118	0.107
		2	0.474	0.452	0.441	0.149	0.123	0.112	0.102
		3	0.438	0.435	0.422	0.132	0.115	0.095	0.095
		average	0.460	0.446	0.433	0.142	0.123	0.108	0.101
		SD	0.019	0.010	0.010	0.009	0.008	0.012	0.006
Sandy-loam clay	0	1	0.451	0.430	0.409	0.228	0.160	0.110	0.100
		2	0.447	0.434	0.403	0.226	0.154	0.106	0.096
		3	0.252	0.247	0.238	0.110	0.079	0.056	0.055
		average	0.383	0.370	0.350	0.188	0.131	0.091	0.084
		SD	0.114	0.107	0.097	0.067	0.045	0.030	0.025
	50	1	0.467	0.456	0.425	0.189	0.132	0.111	0.101
		2	0.459	0.462	0.419	0.185	0.140	0.117	0.106
		3	0.465	0.467	0.412	0.174	0.130	0.098	0.095
		average	0.464	0.462	0.419	0.183	0.132	0.109	0.101
		SD	0.004	0.006	0.007	0.008	0.008	0.010	0.006
	100	1	0.496	0.47	0.451	0.169	0.124	0.115	0.105
		2	0.498	0.466	0.443	0.165	0.132	0.119	0.108
		3	0.486	0.448	0.435	0.152	0.115	0.102	0.092
		average	0.493	0.461	0.443	0.162	0.124	0.112	0.102
		SD	0.006	0.012	0.008	0.009	0.009	0.009	0.009

cont. Tab. 2

Soil	Sludge portion ($Mg·ha^{-1}$)	Repetitions	Volumetric water content ($cm^3·cm^{-3}$) at p*F*						
			0	1.33	1.94	2.89	3.33	4.20	4.70
	200	1	0.531	0.499	0.469	0.144	0.120	0.117	0.106
		2	0.535	0.503	0.467	0.150	0.122	0.111	0.101
		3	0.528	0.487	0.467	0.145	0.128	0.094	0.095
		average	0.531	0.496	0.468	0.146	0.123	0.107	0.101
		SD	0.004	0.008	0.001	0.003	0.004	0.012	0.006
Clay silt	0	1	0.451	0.476	0.459	0.132	0.123	0.117	0.106
		2	0.527	0.482	0.459	0.136	0.121	0.121	0.110
		3	0.529	0.473	0.448	0.125	0.115	0.108	0.098
		average	0.502	0.477	0.455	0.131	0.120	0.115	0.105
		SD	0.044	0.005	0.006	0.006	0.004	0.007	0.006
	50	1	0.514	0.496	0.474	0.133	0.123	0.120	0.109
		2	0.510	0.492	0.480	0.129	0.129	0.128	0.116
		3	0.490	0.475	0.470	0.120	0.125	0.113	0.101
		average	0.504	0.488	0.474	0.127	0.126	0.120	0.109
		SD	0.015	0.011	0.006	0.007	0.003	0.008	0.008
	100	1	0.538	0.536	0.501	0.140	0.131	0.129	0.117
		2	0.544	0.530	0.497	0.138	0.131	0.127	0.115
		3	0.548	0.521	0.512	0.125	0.124	0.113	0.104
		average	0.543	0.529	0.503	0.134	0.129	0.123	0.112
		SD	0.005	0.008	0.008	0.008	0.004	0.009	0.007
	200	1	0.589	0.571	0.546	0.153	0.141	0.133	0.121
		2	0.595	0.569	0.552	0.155	0.137	0.139	0.126
		3	0.605	0.559	0.525	0.135	0.128	0.125	0.125
		average	0.596	0.566	0.541	0.148	0.135	0.132	0.124
		SD	0.008	0.006	0.014	0.011	0.007	0.007	0.003
Sludge	–	1	0.884	0.868	0.812	0.514	0.351	0.230	0.209
		2	0.876	0.868	0.818	0.512	0.345	0.226	0.205
		3	0.905	0.866	0.825	0.489	0.320	0.201	0.198
		average	0.888	0.867	0.818	0.505	0.339	0.219	0.204
		SD	0.015	0.001	0.007	0.014	0.016	0.016	0.006

Explanations: *SD* = standard deviation.
Source: own study.

the ANOVA test to identify sources of population variation and assess statistical significance.

In Table 4 there were presented parameters for the van Genuchten model for the investigated soils and in Figures 1a–c the soil water characteristic curves. The conducted analyses for loose sand showed a soil quality *S*-index of 0.018, for loose sand with a sewage sludge portion of 50 $Mg·ha^{-1}$ – 0.026, for loose sand with a sewage sludge portion of 100 $Mg·ha^{-1}$ – 0.032, and for loose sand with a sewage sludge portion of 200 $Mg·ha^{-1}$ – 0.042 (Tab. 5). For sandy loam, the soil quality *S*-index was 0.045, for sandy loam with a sewage sludge dose of 50 $Mg·ha^{-1}$ – 0.075, for sandy loam with a sewage sludge portion of 100 $Mg·ha^{-1}$ – 0.089, and for sandy loam with a sewage sludge portion of 200 $Mg·ha^{-1}$ – 0.122 (Tab. 5). For clay silt, the soil quality *S*-index was 0.051, for clay silt with a sewage sludge portion of 50 $Mg·ha^{-1}$ – 0.087, for clay silt with a sewage sludge portion of 100 $Mg·ha^{-1}$ – 0.110, and for clay silt with a sewage sludge portion of 200 $Mg·ha^{-1}$ – 0.137 (Tab. 5). For sewage sludge, the soil quality *S*-index was 0.157 (Tab. 5).

Statistical analysis (Tab. 2) showed that the addition of sewage sludge significantly affects soil water retention, but this effect is strongly dependent on soil type and water potential (p*F*).

In the case of loose sand soil, the addition of sludge significantly increased water content at all p*F* values analysed. High *F* statistics and very low *p* values indicate a strong and unambiguous effect of sludge on improving the water properties

Table 3. Results of statistical analysis of data using the ANOVA test

Soil	p*F*	*F*-value	*p*-value	Significant ($p < 0.05$)
Loose sand	0.00	47.69	<0.0001	yes
	1.33	97.39	<0.0001	yes
	1.94	203.376	<0.0001	yes
	2.89	64.983	<0.0001	yes
	3.33	29.356	0.0001	yes
	4.20	30.301	0.0001	yes
	4.70	33.237	0.0001	yes
Sandy-loam clay	0.00	3.640	0.0639	no
	1.33	2.998	0.0952	no
	1.94	3.235	0.0818	no
	2.89	0.941	0.4651	no
	3.33	0.159	0.9210	no
	4.20	0.894	0.4850	no
	4.70	1.200	0.3700	no
Clay silt	0.00	10.401	0.0039	yes
	1.33	82.444	<0.0001	yes
	1.94	50.940	<0.0001	yes
	2.89	3.584	0.0361	yes
	3.33	5.832	0.0206	yes
	4.20	2.704	0.1159	no
	4.70	5.571	0.0233	no

Explanations: p*F* = soil water potential.
Source: own study.

Table 4. Collected parameters to van Genuchten model

Soil	Sludge portion ($Mg \cdot ha^{-1}$)	Parameters to van Genuchten model			
		α (cm^{-1})	n (–)	θ_s ($cm^3 \cdot cm^{-3}$)	θ_r ($cm^3 \cdot cm^{-3}$)
Loose sand	0	0.02435	1.550	0.321	0.031
	50	0.01665	1.334	0.412	0.054
	100	0.00751	1.332	0.437	0.070
	200	0.00581	1.331	0.471	0.105
Sandy loam clay	0	0.00404	1.316	0.449	0.082
	50	0.00491	1.342	0.463	0.091
	100	0.00593	1.342	0.497	0.106
	200	0.00630	1.395	0.533	0.112
Clay silt	0	0.00581	1.349	0.489	0.114
	50	0.00602	1.352	0.512	0.121
	100	0.00584	1.364	0.541	0.129
	200	0.00584	1.384	0.592	0.132
Sludge	–	0.00247	1.298	0.880	0.197

Explanations: α = parameter related to the air-entry pressure (cm^{-1}), n = empirical parameter to the van Genuchten equation (–).
Source: own study.

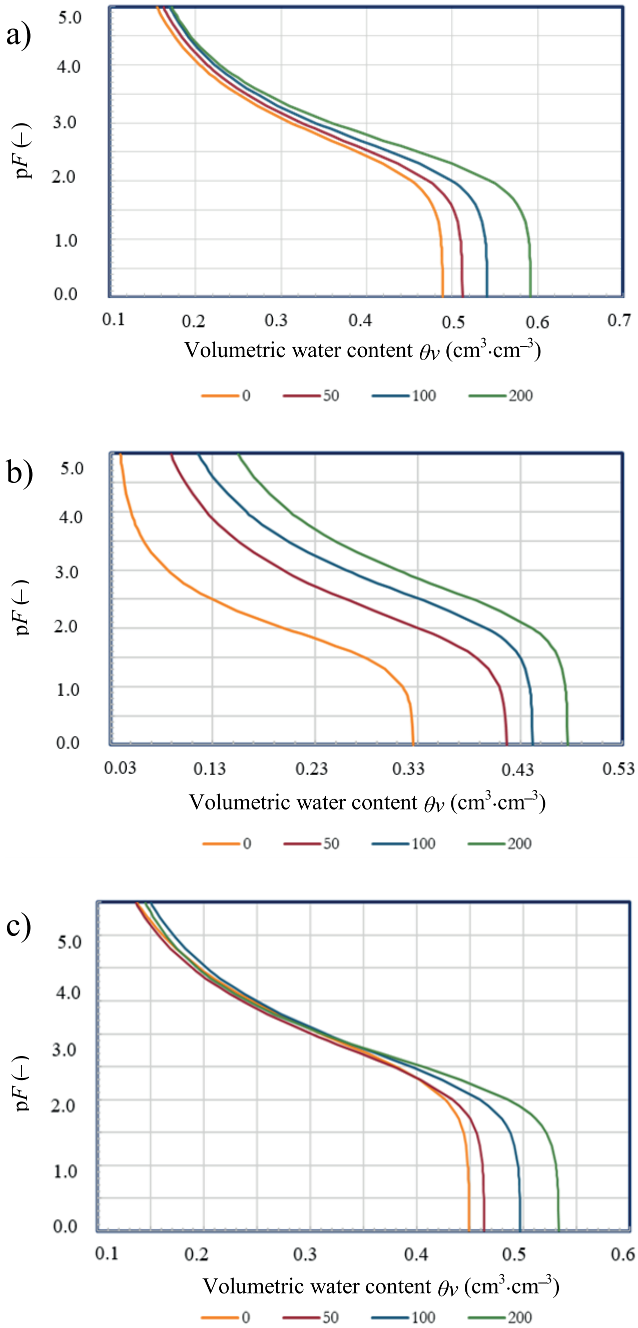

Fig. 1. Soil water characteristic curves for: a) clay silt, b) loose sand, c) sandy loam-clay; source: own study

of this soil. This is consistent with previous studies, which indicate that light soils with low organic matter content and poor structure particularly benefit from the addition of organic matter, such as sewage sludge. Increasing water retention can lead to improved water availability for plants, reduced water losses through infiltration, and increased fertilisation efficiency.

In the case of sandy-loam clay soil, no statistically significant differences in water retention were observed between samples treated with different sludge doses. This may be due to the fact that medium-sized soils already have a relatively good structure and water-holding capacity, making the effect of sludge addition less pronounced. It's worth noting, however, that the lack of statistical significance doesn't mean there's no effect at all – it's

Table 5. The assessment of the soil quality *S*-index and organic matter

Soil	Sludge portion ($Mg·ha^{-1}$)	OM (%)	Quality *S*-index (–)	Increase relative to control sample (%)
Loose sand	0	1.22	0.018	–
	50	1.85	0.026	44.4
	100	2.55	0.032	77.8
	200	3.88	0.042	133.3
Sandy loam clay	0	1.83	0.045	–
	50	2.45	0.075	66.7
	100	3.24	0.089	97.8
	200	4.53	0.122	171.1
Clay silt	0	1.92	0.051	–
	50	2.56	0.087	70.6
	100	3.39	0.110	115.7
	200	4.64	0.137	168.6
Sludge	–	52.7	0.157	–

Explanations: OM = organic matter.
Source: own study.

possible that with a longer incubation period or in field conditions, the effects would be more noticeable.

Clay silt soil showed mixed results. For most p*F* values (especially lower ones, corresponding to plant-available water), sludge addition significantly increased water retention. However, at higher p*F* values (e.g., 2.89 and 4.20), the effect was not statistically significant. This suggests that sludge primarily affects the porosity of macro- and mesopores, rather than micropores, which are responsible for water binding at high potential. In agricultural practice, this means that sludge can improve water availability for plants but does not necessarily increase the soil's total water capacity.

The classification of soil quality according to the *S*-index (Dexter, 2004b) assumes values for mineral soils in Poland ranging from 0.001 to 0.093. In the case of all soils used in the study, there was an increase in the soil quality *S*-index after the application of sewage sludge (Fig. 2). This scale of impact was

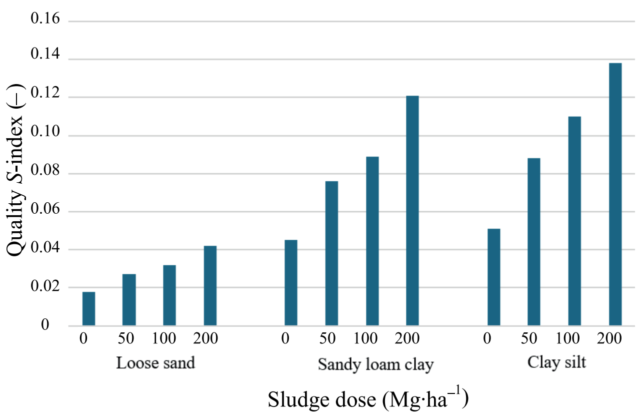

Fig. 2. Soil quality *S*-index; source: own study

significant, particularly for sandy loam and clay silt, while in the case of loose sand, it was somewhat smaller (Fig. 1b).

The introduction of organic matter in the form of sewage sludge in each of the analysed soils resulted in an increase in the quality index by more than 2-fold in relation to the pure soil probe (Fig. 2). The type of soil also has a major impact on water capacity. The course of soil water capacity is presented in the charts (Fig. 1a–c) as a water tension curve depending on the volumetric water content water in the soil. Typically, when referring to the water capacity of the soil, the following relationship is used (in ascending order): sand < silt < clay, which is confirmed by this study. To analogical conclusions came in their work Al-Saeedi *et al.* (2023), where the use of biochar and compost in sandy loam soils led to a significant improvement in water retention and plant-available water.

Figure 1b for loose sand is particularly noteworthy, as the sewage sludge application (see sludge dose in Table 5) significantly increases the water content available (p*F* = 2.0–4.2). The course of the curves is clearly shifted in relation to the axis of the volumetric water content, which confirms the increase in retention capacity in all ranges of water capacity. Characteristic particles of considerable size and a high share in the volume of macropores are typical of light and sandy soils that are characterized by low water capacity. Water rapidly penetrates deep into the soil profile and is not available to plants for a long time, which means that these soils have low water storage potential. The application of sewage sludge as a source of organic matter clearly improved the physicochemical properties of the analysed soils, as evidenced by a more than twofold increase in the soil quality index compared to the control sample. These findings are consistent with the meta-analysis conducted by Paganini *et al.* (2024), which demonstrated that medium and high doses of sewage sludge significantly increase organic matter content and nutrient levels, such as nitrogen and phosphorus, particularly under greenhouse conditions.

In the case of both clay silt (Fig. 1a) and sandy loam-clay (Fig. 1c), the values of potentially available water in the above-mentioned range did not change significantly. Only the capacity of water flowing away by gravity (p*F* = 0.0–2.0) related to atmospheric precipitation, filling the macropore spaces, changed. Sandy soils, poor in organic matter, are particularly noteworthy, where the key factors of plant growth in the soil, i.e. the application of mineral and organic solutions and the stimulation of biological life, through the application of sewage sludge, allow for their restoration to agricultural use as also shown by the research of Cely-Vargas *et. al.* (2024). Increasing the soil capacity and strengthening biological activity, increasing water retention and mineral elements will provide plants with adequate nutrition and water conditions for further plant growth and yield.

CONCLUSIONS

1. Sewage sludge increased the supply of generally available (usable) water for all tested soil species. The application of sewage sludge as a source of organic matter in all analyzed soils resulted in more than a twofold increase in the soil quality *S*-index compared to the control sample. This confirms the positive impact of sewage sludge on the physical properties of soil.

2. Soil type has a significant effect on water holding capacity – the classic relationship sand < silt < clay was confirmed, both in terms of total water retention and the range of plant-available water.
3. The greatest improvement in water retention after sludge application was observed in loose sand, where the water retention curves shifted clearly towards higher water content across the entire p*F* range, especially in the plant-available range (p*F* 0–4.2).
4. In medium and heavy soils (loamy silt, sandy clayey loam), the effect of sludge on plant-available water was less pronounced, but an increase in gravitational water capacity (p*F* 0–4.2) was observed.
5. The use of sewage sludge in soils poor in organic matter can be an effective strategy for improving their water retention properties, increasing biological activity, and restoring them for agricultural use.
6. The increase in water holding capacity and the *S*-index after sewage sludge application may contribute to improved water and nutrient conditions for plants, which in the long term can lead to higher yields and greater stability of agricultural production.

ABBREVIATIONS

α = parameter related to the air-entry pressure (cm^{-1})
BD = bulk density ($g{\cdot}cm^{-3}$)
CAP = common agricultural policy
CEC = cation exchange capacity ($cmol(+){\cdot}kg^{-1}$)
CWH = capillary water-holding capacity (%)
DC = degree of compactness (%)
DCu = desorption curve
DP = deep ploughing
DSP = drought-related stress potential
DRES = rapid soil structure diagnosis
FSQI = field soil quality index (–)
GAEC = good agricultural and environmental conditions
*H*Dexter, H_1, and H_2 = hardening indicators
LLWR = least limiting water range (%)
OC%= organic carbon percentage
OM = organic matter
n = empirical parameter to the van Genuchten equation (–)
NLPCA = nonlinear principal component analysis
NT = no-tillage
OSSS = out on subsoil seeding
PCA = principal component analysis
p*F* = 4.7 (maximum point of hygroscopicity) ($cm^3{\cdot}cm^{-3}$)
PW = percentage of water stress
PGPE = practical guide for participatory assessment of soil quality
PR = penetration resistance (MPa)
RT = rotational tillage
ρ_w = density of soil water ($Mg{\cdot}m^{-3}$)
ρ_o = soil bulk density ($Mg{\cdot}m^{-3}$)
S, S_1, S_2 = soil quality indicators
S-index = Dexter soil quality index (–)
SD = standard deviation
SDI = soil degradation index (–)
SMAF = soil management assessment framework
SQI = soil quality indices
SPQ = soil physical quality
SSC = soil shrinkage curve
SS = subsoiling
SWRC = soil water retention curve
θ_s = volumetric water content at full saturation ($cm^3{\cdot}cm^{-3}$)
θ_r = water in the tank, which causes its movement in the soil ($cm^3{\cdot}cm^{-3}$)
$\theta_{2.0}$ = available water content at suction pressure p*F* = 2.0 (field water capacity) ($cm^3{\cdot}cm^{-3}$)
$\theta_{3.2}$ = volumetric water content at suction pressure p*F* = 3.2 (critical point) ($cm^3{\cdot}cm^{-3}$)
$\theta_{4.2}$ = volumetric water content at suction pressure p*F* = 4.2 (permanent wilting point) ($cm{\cdot}cm^{-3}$)
$\theta_{4.7}$ = volumetric water content at suction pressure p*F* = 4.7 ($cm{\cdot}cm^{-3}$)
VSDD = volumetric soil dry density ($g{\cdot}cm^{-3}$)
WLP = water logging potential (–)
Y = tensile strength (kPa)

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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